# Exploring Geology

Third Draft

November 2006

CHAPTER

# 3 Plate Tectonics

THE SURFACE OF EARTH IS NOTABLE for its dramatic mountains, beautiful plains, and intricate coastlines. Beneath the sea are equally interesting features, such as undersea mountain ranges, deep trenches, and thousands of isolated mountains. In this chapter, we examine the distribution of these features, along with the locations of earthquakes and volcanoes, to explore the theory of plate tectonics.

**On these images of the world**, the land is colored using satellite data overlain on topography, whereas the seafloor is shaded blue according to water depth (lighter blue colors represent shallower water).

**Offshore of western North America** is a long, fairly straight step in the seafloor that trends east-west and ends abruptly at the coastline. North of this step, a curious ridge called the Juan de Fuca Ridge, zigzags across the seafloor.

*What are these features on the seafloor and how did they form?*

**South America is lopsided** because the mountainous Andes flank the western coast, but a wide expanse of lowlands, including the Amazon Basin, makes up the rest of the continent. The western edge of the continent is abrupt and flanked by a deep trench in the Pacific Ocean. The eastern edge of the continent continues well beyond the shoreline and forms a broad bench covered by shallow waters (shown in light blue).

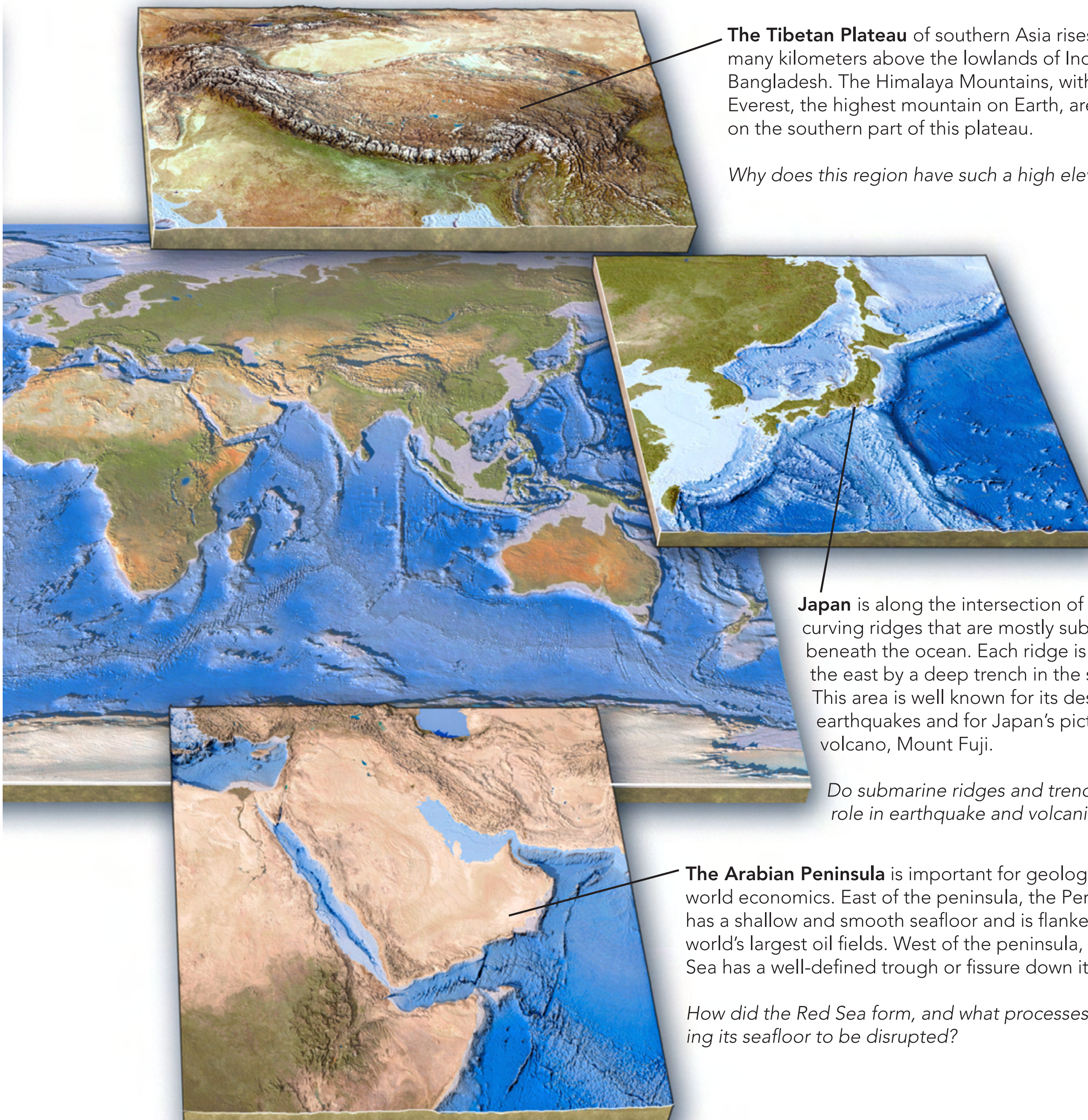
*How did the two sides of the continent come to be so different?*

**A huge mountain range**, longer than any on land, is hidden beneath the waters of the Atlantic Ocean. The part of the range shown here is half way between South America (on the left) and Africa (on the right). South America zigzags across the seafloor, mimicking the shape of the two continents.

*What is this underwater mountain range, and why is it almost exactly in the middle of the ocean?*

## Topics in this Chapter





**The Tibetan Plateau** of southern Asia rises many kilometers above the lowlands of India and Bangladesh. The Himalaya Mountains, with Mount Everest, the highest mountain on Earth, are perched on the southern part of this plateau.

*Why does this region have such a high elevation?*

**Japan** is along the intersection of large, curving ridges that are mostly submerged beneath the ocean. Each ridge is flanked to the east by a deep trench in the seafloor. This area is well known for its destructive earthquakes and for Japan's picturesque volcano, Mount Fuji.

*Do submarine ridges and trenches play a role in earthquake and volcanic activity?*

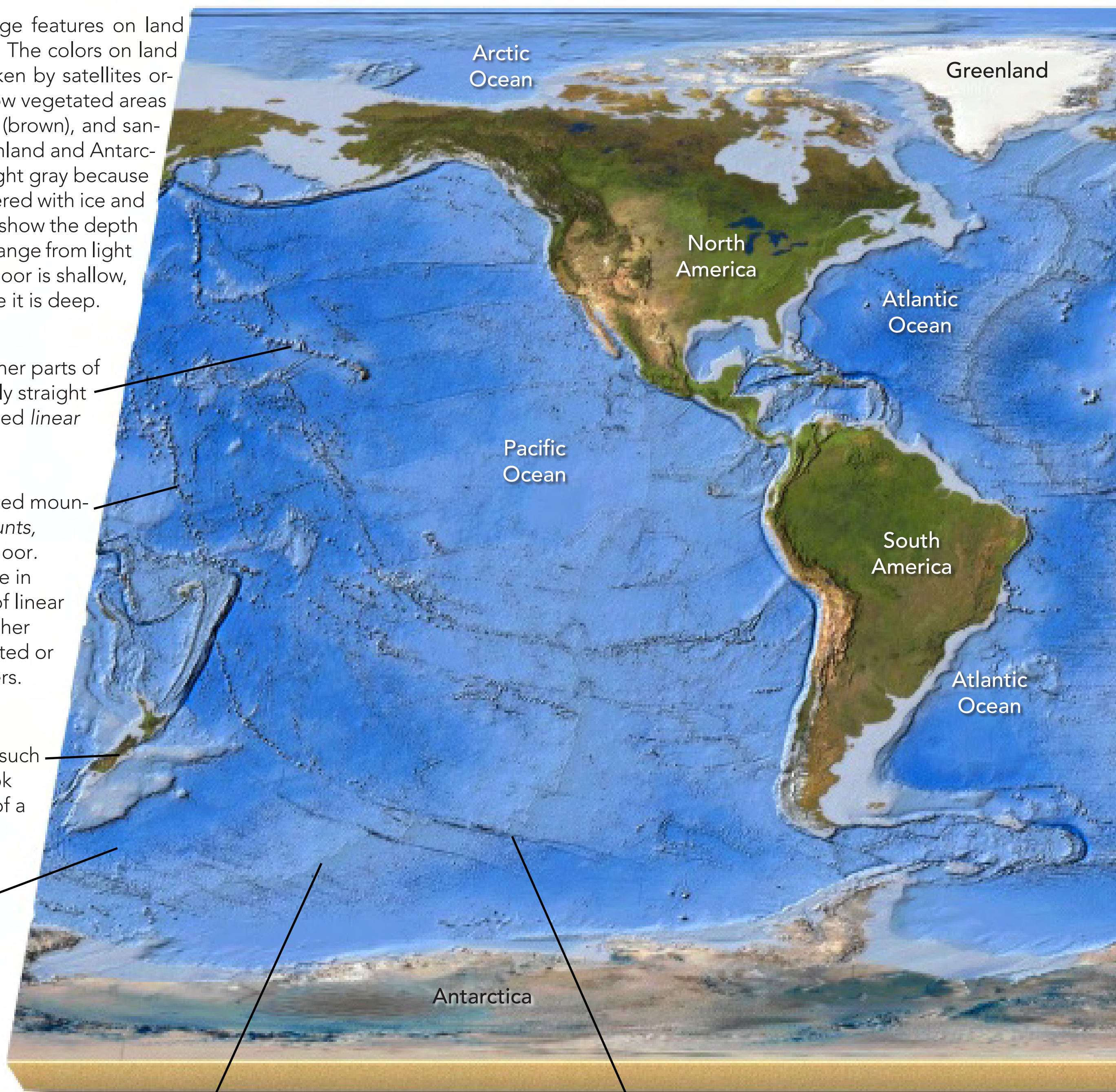
**The Arabian Peninsula** is important for geology and world economics. East of the peninsula, the Persian Gulf has a shallow and smooth seafloor and is flanked by the world's largest oil fields. West of the peninsula, the Red Sea has a well-defined trough or fissure down its center.

*How did the Red Sea form, and what processes are causing its seafloor to be disrupted?*

# What Are the Major Features of Earth?

THE SURFACE OF EARTH has three major types of features: continents, ocean basins, and islands. The continents display a remarkable diversity of landforms, from broad coastal plains to steep, snow-capped mountains. Features of the ocean floor include deep trenches and a submarine mountain range that encircles much of the globe. Some islands are large and isolated, but other islands define arcs, ragged lines, or irregular clusters. What are the characteristics of each type of feature?

This map shows large features on land and on the seafloor. The colors on land are from images taken by satellites orbiting Earth and show vegetated areas (green), rocky areas (brown), and sandy areas (tan). Greenland and Antarctica are white and light gray because they are mostly covered with ice and snow. Ocean colors show the depth of the seafloor and range from light blue where the seafloor is shallow, to darker blue where it is deep.




Hawaii and many other parts of the oceans have fairly straight chains of islands called *linear island chains.*

Numerous submerged mountains, called *seamounts,* exist on the ocean floor. Some seamounts are in long belts as parts of linear island chains, but other seamounts are isolated or form irregular clusters.

Some large islands, such as New Zealand, look like a small version of a continent.

Much of the ocean floor is moderately deep—3 to 5 km—and has a fairly smooth surface. These smooth regions are called *abyssal plains.*

*Mid-ocean ridges* are broad, symmetrical ridges that cross the ocean basins. They are 2 to 3 kilometers higher than the average depth of the seafloor.

Sharp steps in the seafloor, called *oceanic fracture zones,* are at right angles to the mid-ocean ridges.

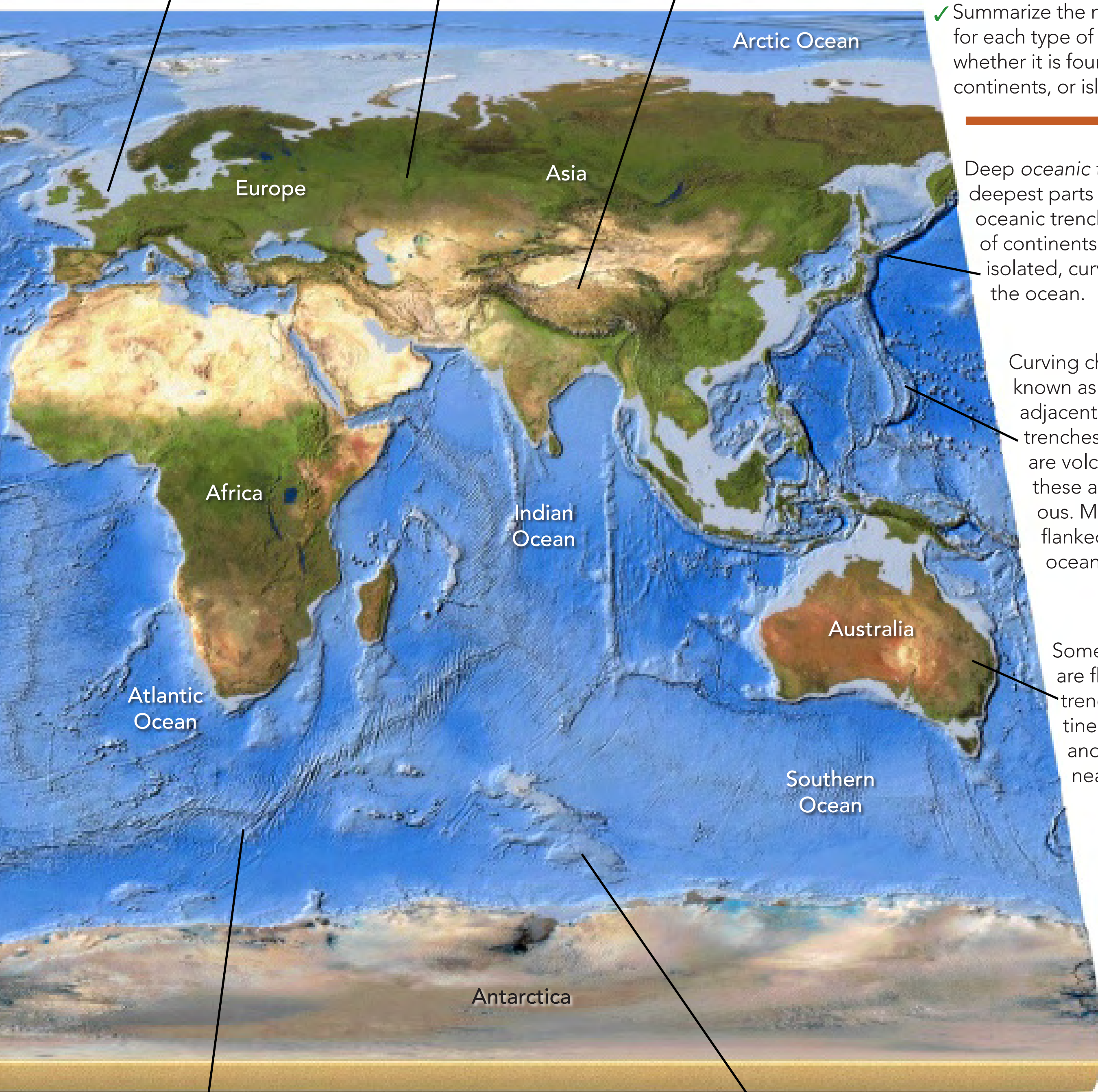
Some continents continue outward from the shoreline under shallow seawater for hundreds of kilometers, forming submerged benches (light blue in this image), known as *continental shelves*. Such shelves surround Great Britain and Ireland.

All of the continents have large regions that are broad plains with gentle topography. Some continents have mountains along their edges or within their interiors.

Most continental areas have elevations of less than 1 to 2 kilometers (3,300 to 6,600 feet). Broad, high regions, called *plateaus*, reach high elevations such as on the Tibetan Plateau of southern Asia.

### Before You Leave This Page Be Able To

- ✓ Identify on a world map the named continents and oceans.
- ✓ Identify on a world map the main types of features on the continents and in the oceans.
- ✓ Summarize the main characteristics for each type of feature, including whether it is found in the oceans, on continents, or islands.




Deep *oceanic trenches* make up the deepest parts of the ocean. Some oceanic trenches follow the edges of continents, whereas others form isolated, curving troughs out in the ocean.

Curving chains of islands, known as *island arcs*, are adjacent to many oceanic trenches. Most of the islands are volcanoes, and many of these are active and dangerous. Most island arcs are flanked on one side by an oceanic trench.

Some continental edges are flanked by oceanic trenches, but other continents, such as Australia and Africa, have no nearby trenches.

Mid-ocean ridges and their associated fracture zones encircle much of the globe and, in the Atlantic and Southern Oceans, occupy a position halfway between the continents on either side.

Within the oceans are several broad, elevated regions called *oceanic plateaus*. The Kerguelen Plateau near Antarctica is one example.

# Where Do We Find Earthquakes, Volcanoes, and Mountain Belts?

**EARTHQUAKES, VOLCANOES, AND MOUNTAIN BELTS are spectacular expressions of geology. Many of these features are in remote, far-off places, but some are close to where we live. The distribution of earthquakes, volcanoes, and mountain belts is not random. It instead defines clear patterns that reflect important, large-scale Earth processes.**

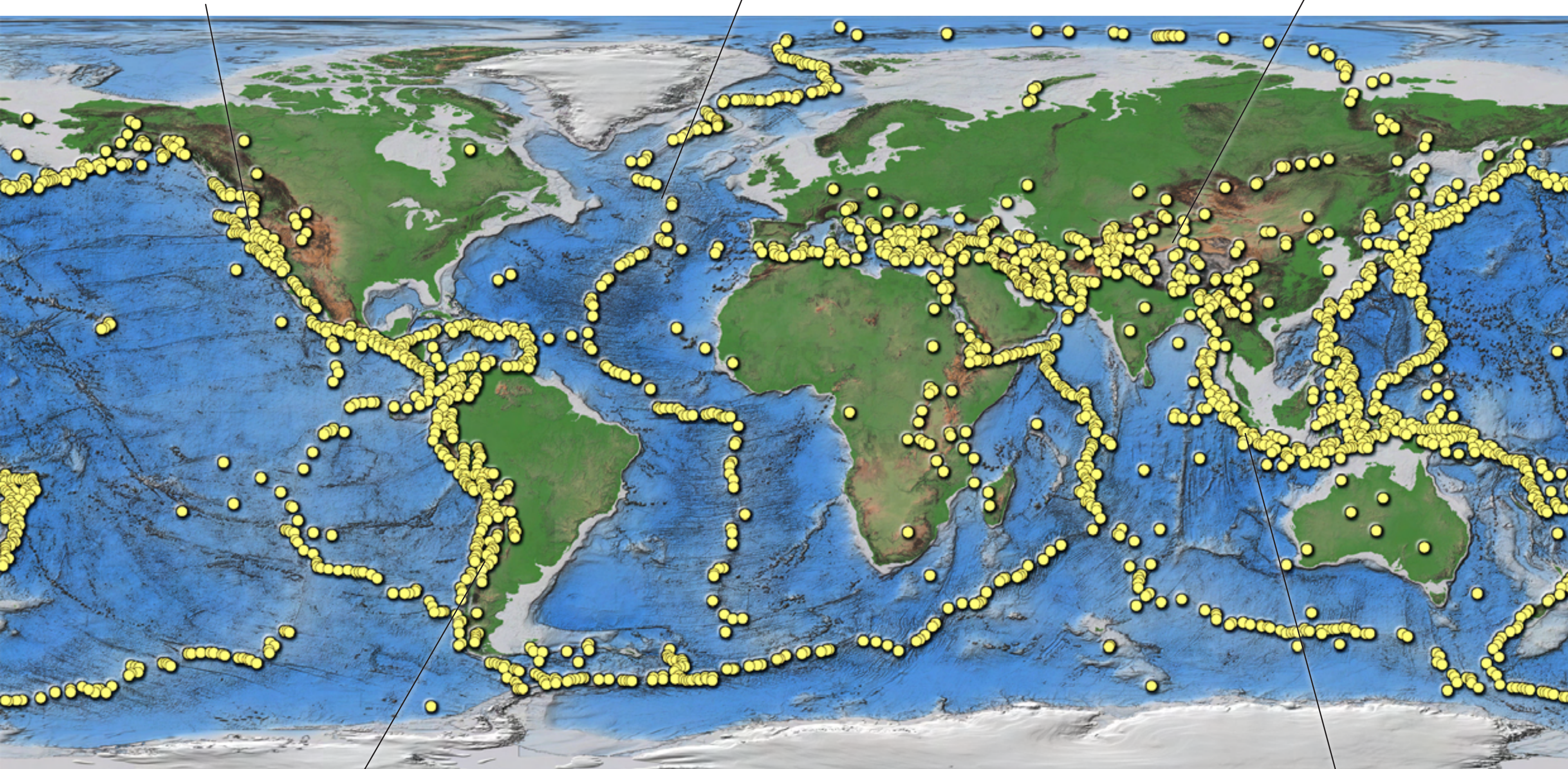
## A Where Do Most Earthquakes Occur?

On this map, yellow circles show the locations of moderate to strong earthquakes that occurred between 1973 and 2000. Observe the distribution of earthquakes on this map before reading on. What patterns do you notice? Which regions have many earthquakes? Which regions have few or no earthquakes?

Earthquakes are not distributed uniformly across the planet. Instead, they are mostly concentrated in discrete belts, such as the one that runs along the western coast of North America.

Most earthquakes in the oceans occur along the winding crests of mid-ocean ridges. Where the ridges curve or zigzag, so does the pattern of earthquakes.

In several regions, earthquakes are abundant in the middle of a continent. Such earthquake activity happens in parts of the Middle East and especially in China and Tibet.



Some continental edges have many earthquakes, but others have few. In South America and North America, earthquakes are common along the western coasts, but not along the eastern coasts.

Earthquakes are not common in the interiors of some continents, such as in eastern North America, eastern South America, western Africa, and the northern parts of Asia and Europe.

Earthquakes are common along the curving oceanic trenches and the associated island arcs. In fact, many of the world's largest and most deadly earthquakes occur in regions near an oceanic trench. A recent example was the large earthquake that unleashed deadly waves in the Indian Ocean in December of 2004.

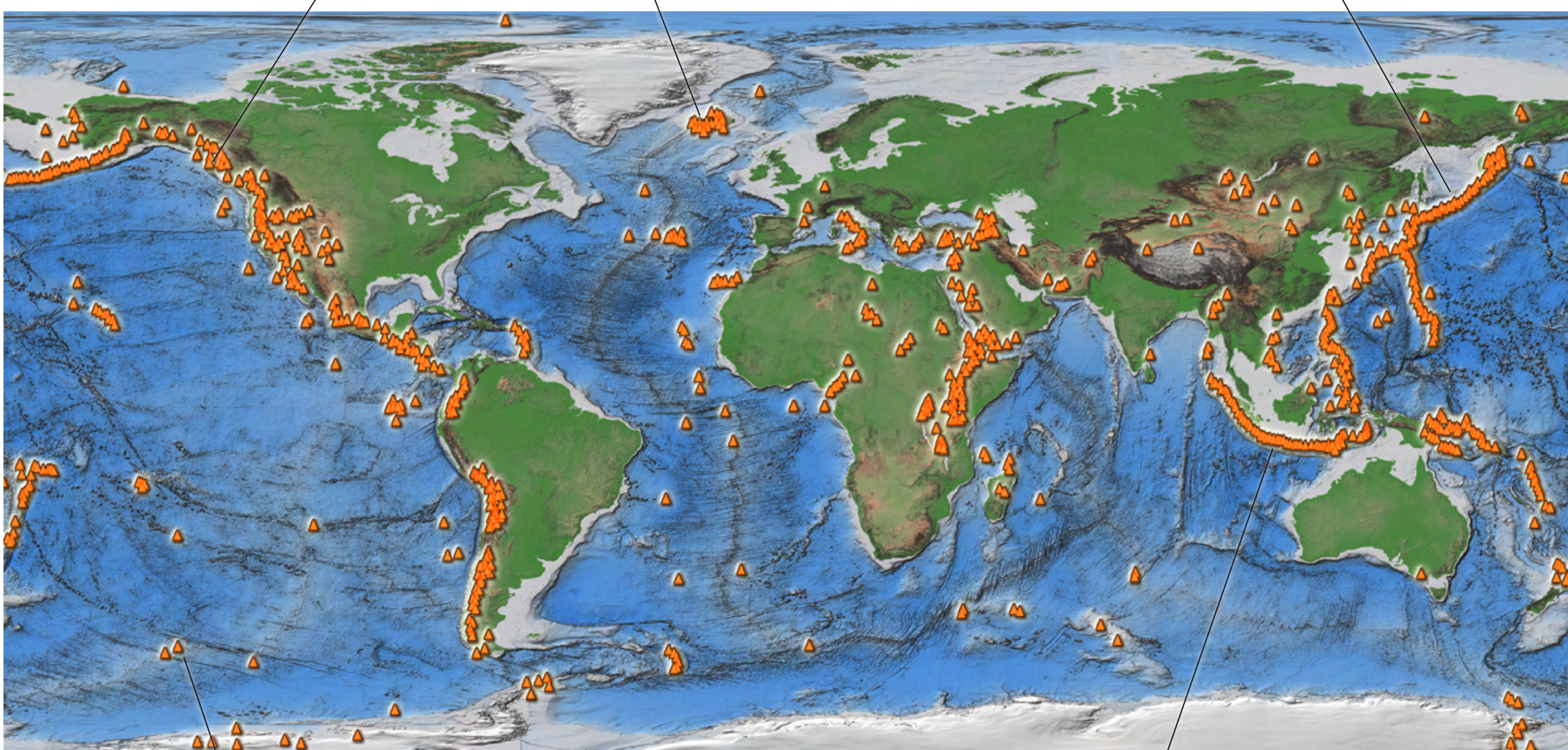
## B Which Areas Have Volcanoes?

On the map below, orange triangles show the locations of recently active volcanoes. Observe the distribution of volcanoes and note any patterns. Which areas have many volcanoes? Which areas have none?

Volcanoes, like earthquakes, are not distributed everywhere, but commonly occur in belts. One belt extends along the western coasts of North and South America.

There are clusters of volcanoes in the oceans such as near Iceland. Iceland is a large volcanic island along the mid-ocean ridge in the North Atlantic Ocean.

Volcanoes occur along the western edge of the Pacific Ocean, extending from north of Australia through the Philippines and Japan.

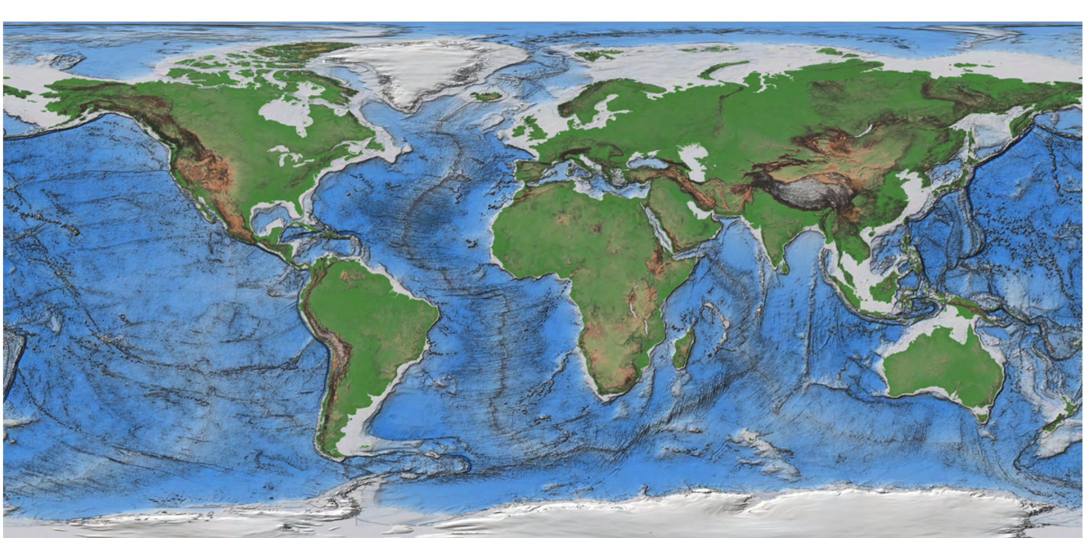


Beneath the oceans are many volcanic mountains, only the largest of which are shown here. Volcanic activity also occurs along most of the mid-ocean ridge.

Some volcanoes form in the middle of continents, such as in China and the eastern part of Africa.

Volcanoes, many of which are active, define island arcs, such as the curving island chain of Java.

The map below is the base map on which the earthquakes and volcanoes are plotted. The colors show elevation, with high elevations in brown and low elevations in green. The blue colors of the oceans darken with depth. Using the three maps, compare the distributions of earthquakes, volcanoes, and elevations. Try to identify areas where there are (1) mountains but no earthquakes, (2) mountains but no volcanoes, and (3) earthquakes but no volcanoes. Make a list of these areas, or mark the areas on a map.



### Before You Leave This Page Be Able To

- ✓ Show on a relief map of the world the major belts of earthquakes and volcanoes.
- ✓ Describe how the distribution of volcanoes corresponds to that of earthquakes.
- ✓ Compare the distributions of earthquakes, volcanoes, and elevations.

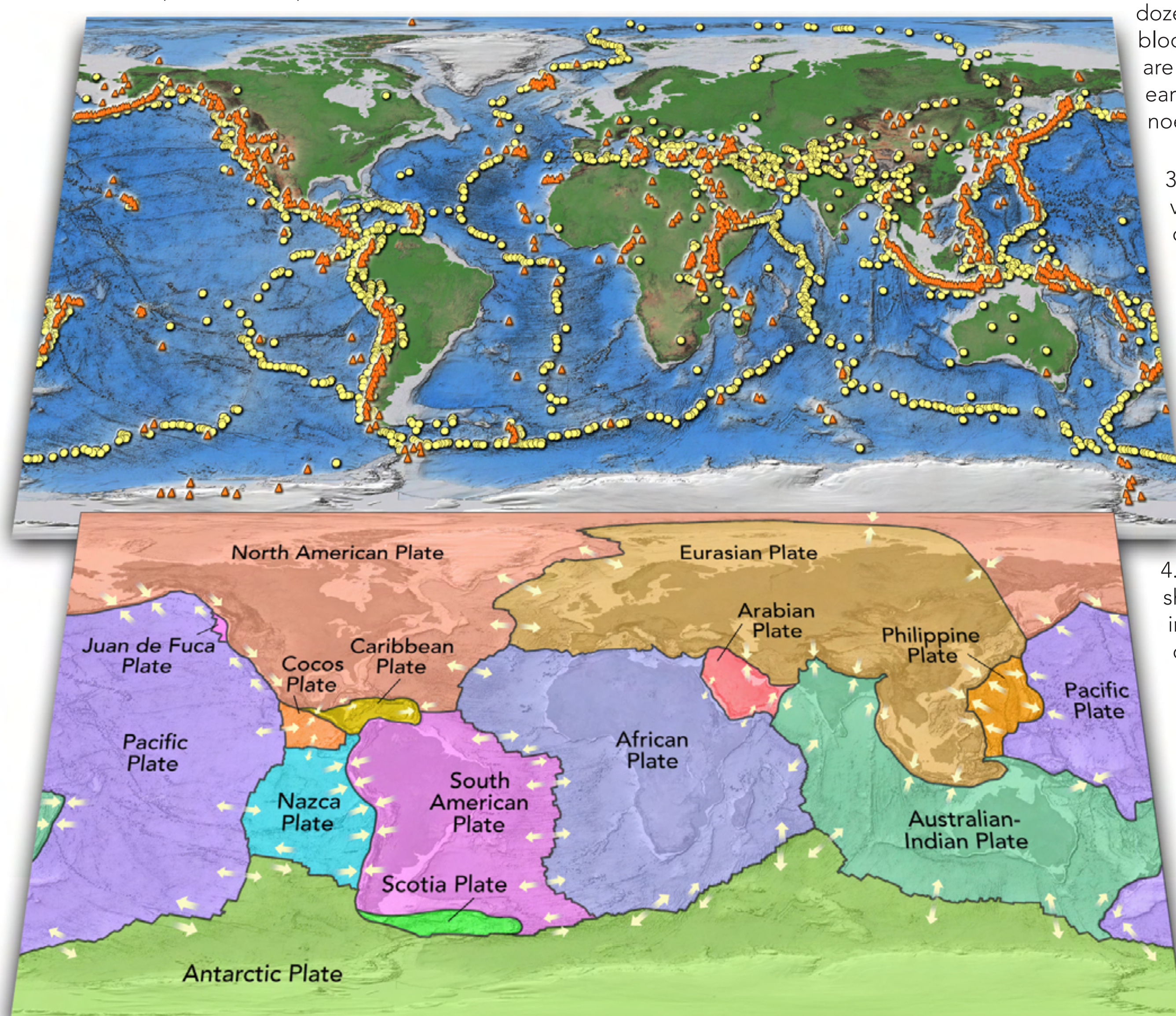
# What Causes Tectonic Activity to Occur in Belts?

WHY DO EARTHQUAKES AND VOLCANOES occur in belts around Earth's surface? Why are there vast regions that have comparatively little of this activity? What causes this observed pattern? The best explanation is the *theory of plate tectonics*.

## A What Do Earthquake and Volcanic Activity Tell Us About Earth's Lithosphere?

1. Examine the map below, which shows earthquakes (yellow circles) and volcanoes (orange triangles). After noting the obvious patterns, compare this map with the map beneath it and then read the associated text.

2. On the upper map, there are large regions that have few earthquakes and volcanoes. These regions are relatively stable and intact blocks. There are a dozen or so of these blocks, whose edges are defined by belts of earthquakes and volcanoes.




3. Earthquakes, volcanism, and other processes that deform Earth's crust and upper mantle are called *tectonic activity*, or simply *tectonics*. The yellow and orange areas on the map are said to have *active tectonics*.

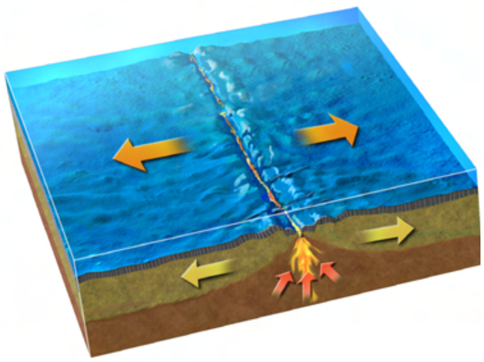
4. This lower map shows how geologists interpret the pattern on the upper map. Earth's upper strong layer, called the *lithosphere*, is broken into a dozen or so fairly rigid blocks, called *tectonic plates*. This map shows the names and boundaries of the larger plates. This book refers to these plates throughout its chapters, so it is worthwhile spending a little time learning the names of the larger plates.

5. Compare the two maps and note how the distribution of tectonic activity, especially earthquakes, outlines the shapes of the plates. Earthquakes are a better guide to plate locations than are volcanoes. Most volcanoes do lie near plate boundaries, but many plate boundaries have no volcanoes. Some volcanoes and earthquakes occur in the middle of plates.

## B How Do Plates Move Relative to One Another?

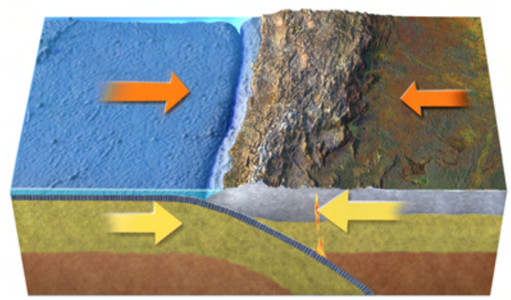
The boundary between two plates has earthquakes and other tectonic activity because the plates are moving *relative to one another*. For this reason, we talk about *relative motion* of plates across a plate boundary. Two plates can *move away*, *move toward*, or *move sideways* relative to one another. Based on these types of relative motion, three types of plate boundaries are defined: *divergent*, *convergent*, and *transform*.

### Divergent Boundary



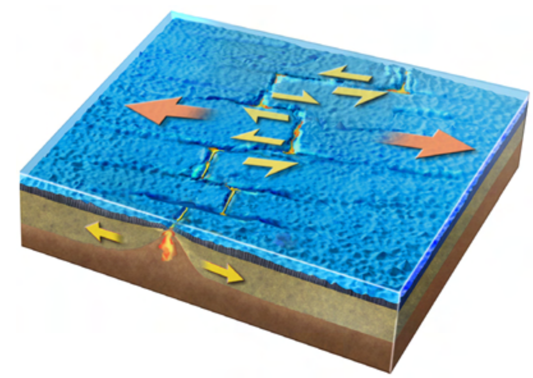
At a *divergent boundary*, two plates move apart relative to one another.

### Convergent Boundary



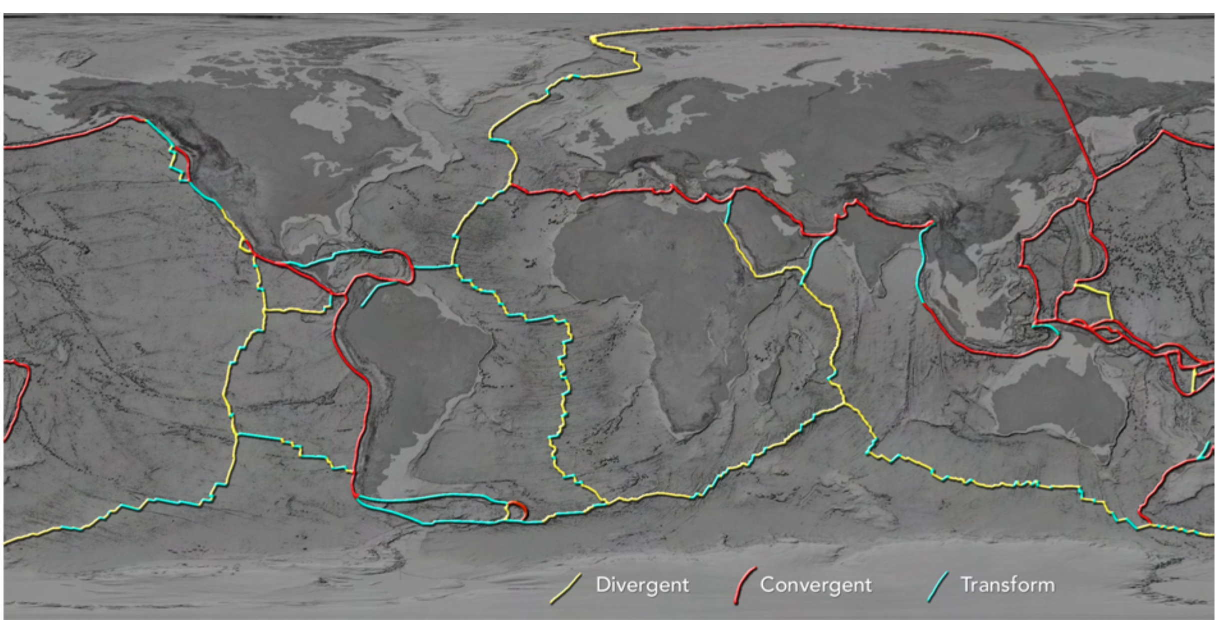
At a *convergent boundary*, two plates move toward one another.

### Transform Boundary



At a *transform boundary*, two plates move horizontally past one another.

## C Where Are the Three Types of Plate Boundaries?




On this map, plate boundaries are colored according to type. Compare this map with the top map in *Part A* and with those shown earlier in the chapter. Determine whether each type of plate boundary is *generally* associated with each of the following features:

- Earthquakes
- Volcanoes
- Mountain Ranges
- Mid-Ocean Ridges
- Oceanic Trenches

## Rigid and Not-So-Rigid Plates

Plate tectonics, in its most strict sense, would have purely rigid plates with tectonic activity happening only at the boundaries. Based on the maps of earthquakes and volcanoes, this is not precisely true. Most tectonic activity occurs at or near inferred plate boundaries, but some tectonic activity happens well away from plate boundaries. Clearly, Earth is more complicated than the plate-tectonic ideal. This is largely because some parts of the lithosphere are weaker than are other parts. Forces can be transmitted through the strong parts, causing the weaker parts to break and slip. In a few cases, tectonic activity within a plate indicates that a new plate boundary may be forming.

### Before You Leave This Page Be Able To

- ✓ Explain what plate tectonics is and the three types of plate boundaries.
- ✓ Compare the three types of plate boundaries with the distributions of earthquakes, volcanoes, mountain belts, mid-ocean ridges, and trenches.

# What Happens When Plates Move Apart?

AT MID-OCEAN RIDGES, Earth's tectonic plates are moving apart (diverging), forming new oceanic lithosphere. Such boundaries are the sites of numerous small earthquakes and submarine volcanism. Divergent motion can split a continent into two pieces and form a new ocean basin as the rifted pieces move apart.

## A How Do Mid-Ocean Ridges Form?

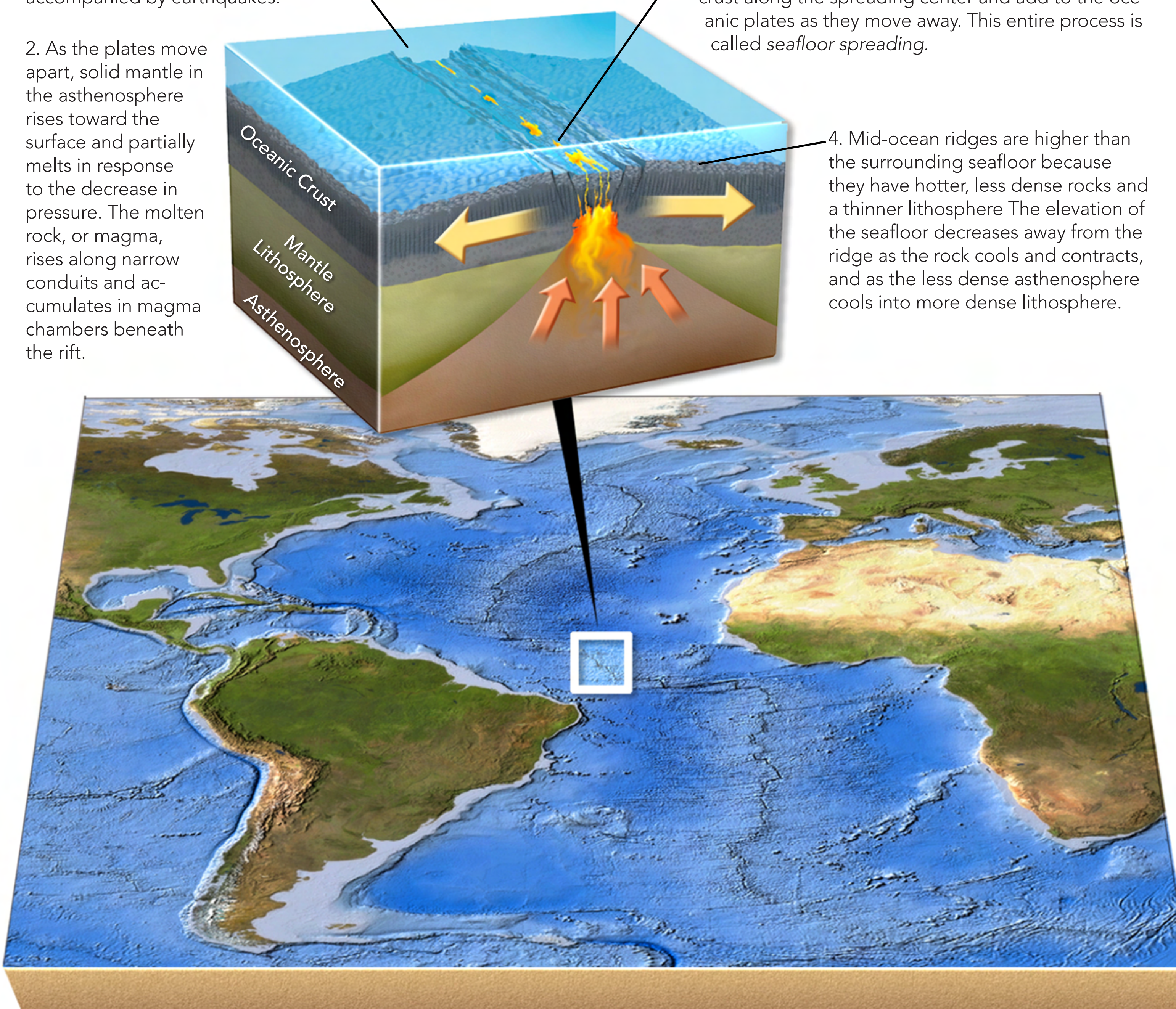
*Mid-ocean ridges* mark divergent boundaries in the ocean where two oceanic plates move apart relative to one another. These boundaries are also called *spreading centers* because of the way the plates spread apart.

1. A narrow trough, called a *rift*, runs along the axis of the mid-ocean ridge. The rift forms as large blocks of crust are down-faulted to accommodate spreading. The faulting is accompanied by earthquakes.

2. As the plates move apart, solid mantle in the asthenosphere rises toward the surface and partially melts in response to the decrease in pressure. The molten rock, or magma, rises along narrow conduits and accumulates in magma chambers beneath the rift.

3. Along the rift, magma erupts onto the seafloor as submarine lava flows, while other magma solidifies at depth. These magmatic additions create new oceanic crust along the spreading center and add to the oceanic plates as they move away. This entire process is called *seafloor spreading*.

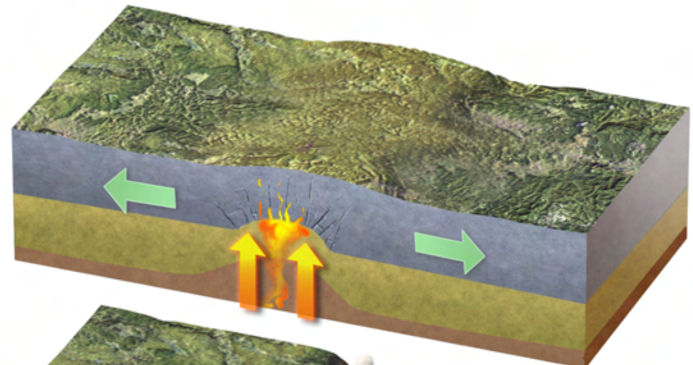
4. Mid-ocean ridges are higher than the surrounding seafloor because they have hotter, less dense rocks and a thinner lithosphere The elevation of the seafloor decreases away from the ridge as the rock cools and contracts, and as the less dense asthenosphere cools into more dense lithosphere.



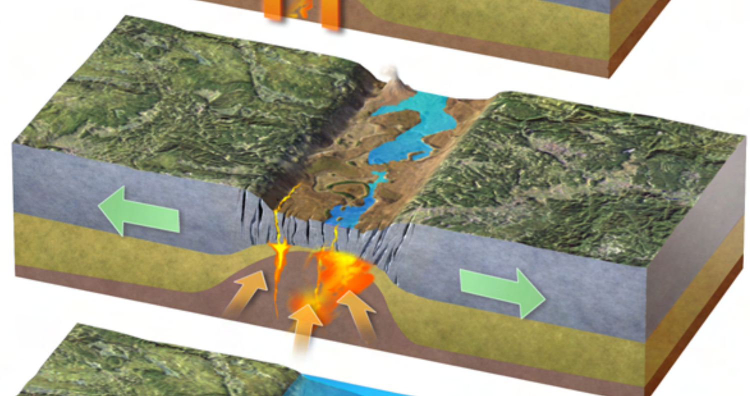
## B What Happens When Divergence Splits a Continent Apart?

A divergent boundary can form within a continent, causing a *continental rift* such as the *Great Rift Valley* in East Africa. Such rifting, if it continues, leads to seafloor spreading and the formation of a mid-ocean ridge and new ocean basin, following the progression shown here.

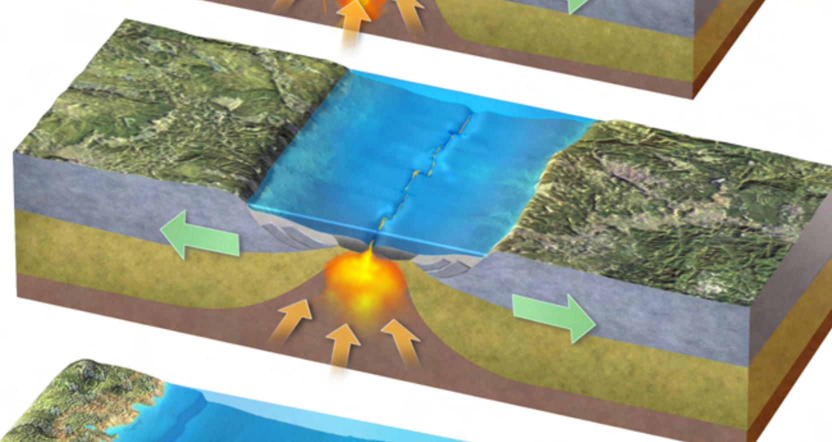
The initial stage of continental rifting commonly includes broad uplift of the land surface as mantle-derived magmas ascend into and heat the crust. The magmas can melt parts of the continental crust, producing additional magma. Heating of the crust causes it to expand, which results in further uplift.



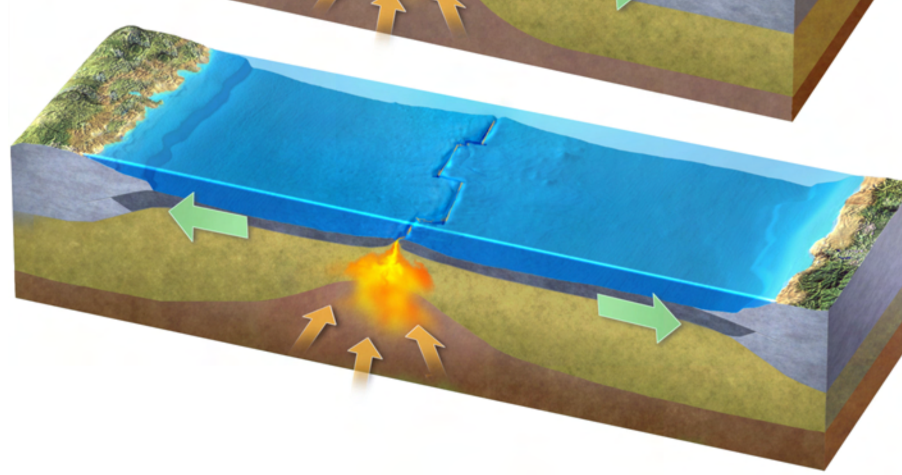
Stretching of the crust causes large crustal blocks to drop down along faults, forming a *continental rift*. The down-dropped blocks are *basins* that can trap sediment and water. At depth, rifting causes solid mantle material in the asthenosphere to continue flowing upward and partially melt. The resulting magma erupts from volcanoes and long fissures on the surface, or can solidify in the subsurface. The entire crust thins as it is pulled apart, so the rifted region will drop in elevation as it cools. A modern example of this stage is the *East African Rift*.



If rifting continues, the continent splits into two pieces and a narrow ocean basin forms by the onset of seafloor spreading. A modern example of this stage is the *Red Sea*, which formed when the Arabian Peninsula rifted away from Africa.



With continuing seafloor spreading, the ocean basin becomes progressively wider, eventually becoming a broad ocean like the modern-day *Atlantic Ocean*. The Atlantic Ocean basin formed when North and South America rifted away from Europe and Africa, following the sequence shown here. Sea-floor spreading continues today along the ridge in the middle of the Atlantic Ocean, transporting the Americas farther away from Europe and Africa.



### Before You Leave This Page Be Able To

✓ Sketch, label, and explain an oceanic divergent boundary.

✓ Sketch, label, and explain a divergent boundary within a continent (i.e., a continental rift).

✓ Sketch, label, and explain how continental rifting can lead to the formation of a new ocean basin.

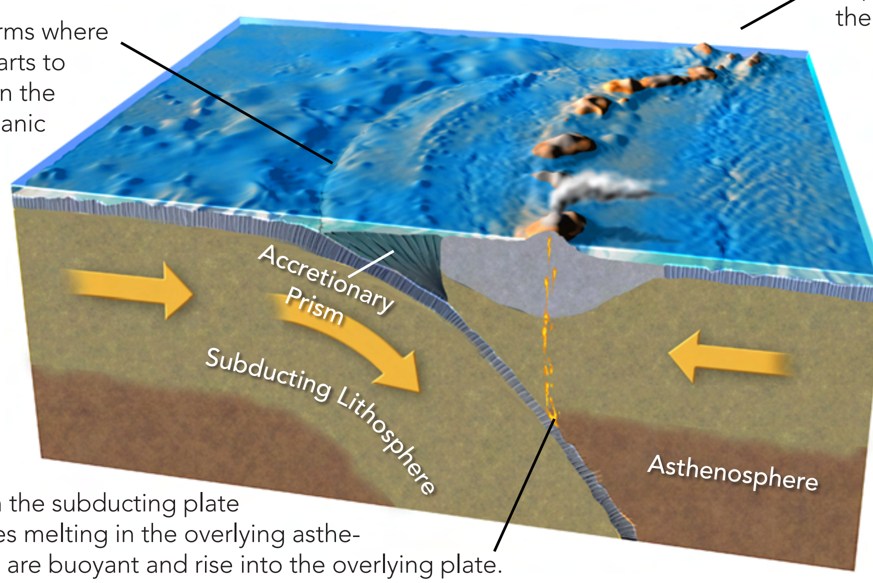
# What Happens When Plates Converge?

CONVERGENT BOUNDARIES FORM where two plates move together. Convergence of plates can occur between two oceanic plates, between an oceanic plate and a continental plate, or between two continental plates. Oceanic trenches, island arcs, and many of Earth's largest mountain belts form at convergent boundaries. Many of Earth's most dangerous volcanoes and largest earthquakes also occur here.

## A What Happens When Two Oceanic Plates Converge?

1. Convergence of two oceanic plates form an *ocean-ocean convergent boundary.* One plate is pulled down beneath the other plate along an inclined zone marked by earthquakes. This process of one plate sliding beneath another plate is called *subduction.*

2. An oceanic trench forms where the subducting plate starts to bend down. Sediment in the trench and slices of oceanic crust are scraped off, forming a wedge of highly sheared rocks called an *accretionary prism*. This name signifies that material is being added (accreted) over time to the wedge-shaped region.




3. Chemical reactions in the subducting plate release water that causes melting in the overlying asthenosphere. The magmas are buoyant and rise into the overlying plate.

4. Some magmas erupt onto the surface from dangerous, explosive volcanoes. Eventually, the erupted lava and volcanic ash construct a curving belt of islands that rise above sea level as an *island arc.* An example is the arc-shaped *Aleutian Islands* chain of Alaska.

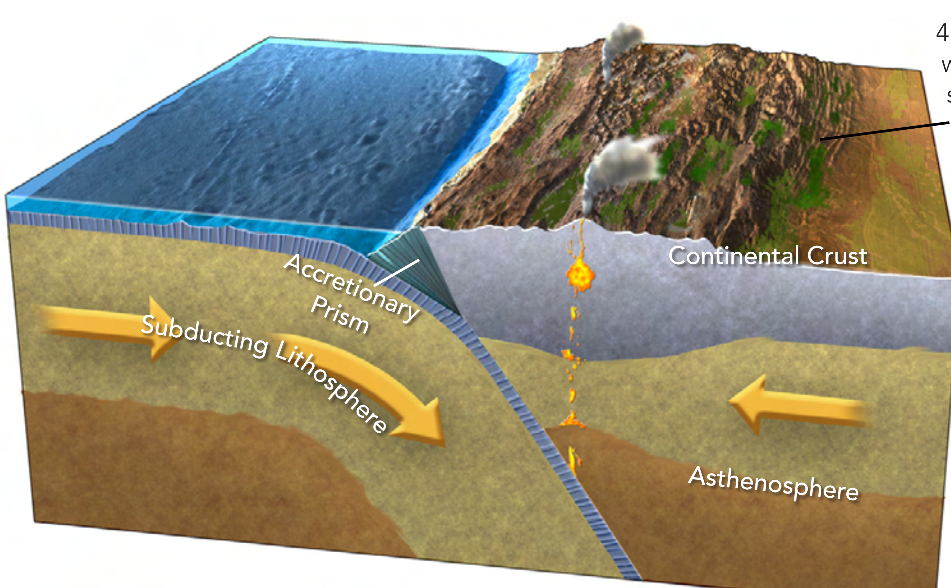
5. Some magmas solidify at depth, also adding to the volume of the crust. Over time, the crust gets thicker and volcanoes build together to form a more continuous strip of land, such as along the Java region of Indonesia.

## B What Happens When an Oceanic Plate and a Continental Plate Converge?

1. Convergence between an oceanic and a continental plate forms an *ocean-continent convergent boundary.* Along this boundary, the denser oceanic plate is subducted beneath the more buoyant continental plate.

2. An oceanic trench marks the plate boundary and receives sediment from the adjacent continent. This sediment and material scraped off the oceanic plate form an *accretionary prism.*

3. Volcanoes form on the surface of the overriding continental plate. These volcanoes erupt volcanic ash and lava onto the landscape and pose a hazard for people who live here. Examples include the large volcanoes atop the *Cascade Range* of the Pacific Northwest and those within the Andes Mountains of South America.

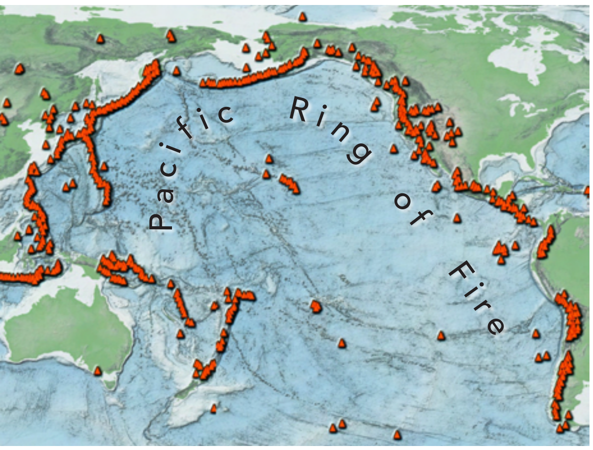



4. Compression associated with the convergent boundary squeezes the crust for hundreds of kilometers into the continent. The crust deforms and thickens forming a high mountain range, such as the *Andes.*

5. Magmas form by melting of the asthenosphere above the subduction zone. Some magma rises into the overlying continental crust, while other magma solidifies at depth.

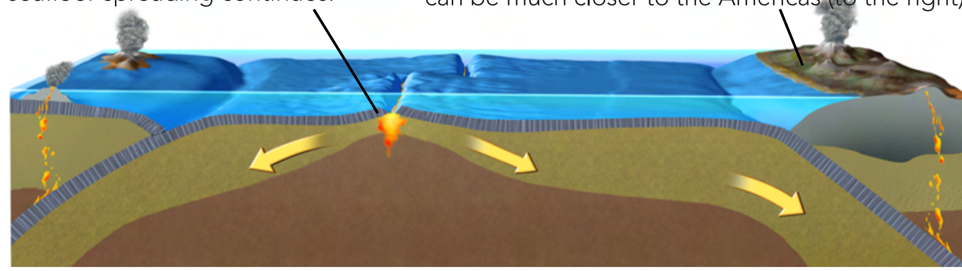
## C What Causes the Pacific Ring of Fire?

Volcanoes surround the Pacific Ocean, forming the *Pacific Ring of Fire*, as shown in the map below. The volcanoes extend from the southwestern Pacific, through the Philippine Islands, Japan, and Alaska, and down the western coasts of the Americas. The Ring of Fire results from subduction on both sides of the Pacific Ocean.



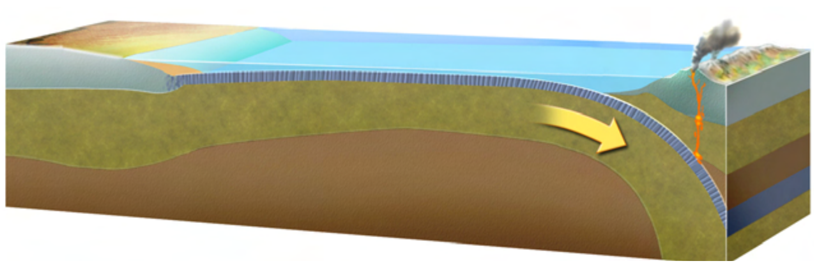

New oceanic lithosphere forms along a mid-ocean ridge, called the *East Pacific Rise*. Once formed, the new lithosphere moves away from the ridge as seafloor spreading continues.

Subduction of this oceanic lithosphere occurs along both sides of the Pacific Ocean, producing oceanic trenches on the seafloor and volcanoes on the overriding plates. The Pacific Ocean is wider than shown here and the spreading center can be much closer to the Americas (to the right).

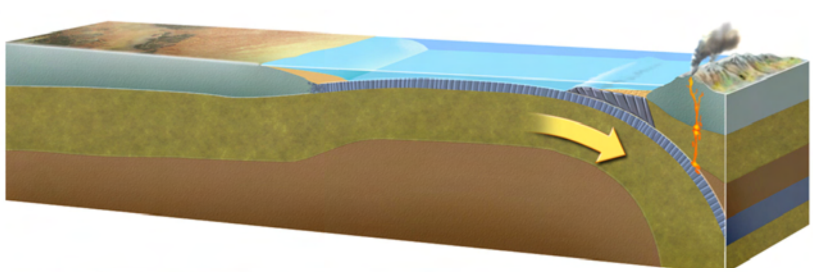


## D What Happens When Two Continents Collide?

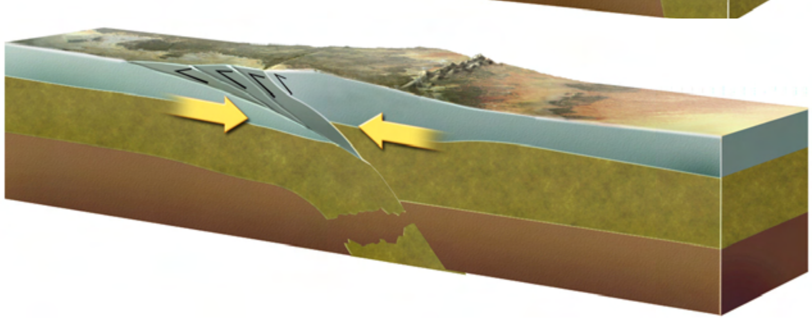
Two continental masses may converge along a *continent-continent convergent boundary*. This type of boundary is commonly called a *continental collision*.



The plate on the left is partly oceanic and partly continental, and the oceanic part can be subducted at a convergent boundary. For a continental collision to occur, the overriding plate (on the right) must also be a continental plate.



Subduction of the oceanic part of the plate may bring the continent progressively closer to the trench and the convergent boundary. Note that all magmatic activity occurs in the overriding plate, not on the approaching continent.



When the continent arrives at the boundary, it is dragged partially under the other continent or simply clogs the subduction zone as the two continents collide. The continent cannot be subducted deeply into the asthenosphere because it is too buoyant. Collision can form enormous mountain belts and high plateaus, such as the Himalaya Mountains and Tibetan Plateau of southern Asia. In this region, continental crust of India collided with and was shoved beneath the southern edge of Asia.

**Before You Leave This Page Be Able To**

✓ Sketch, label, and explain the three types of convergent boundaries, including the features and processes associated with each.

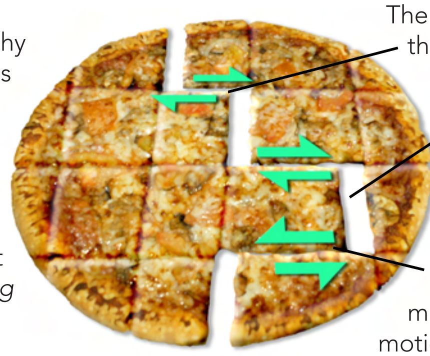
✓ Sketch, label, and explain the steps leading to a continental collision (continent-continent convergent boundary).

# What Happens When Plates Slip Past One Another?

AT TRANSFORM BOUNDARIES, PLATES SLIP HORIZONTALLY past each other. In the oceans, such boundaries are *transform faults* and generally are associated with mid-ocean ridges. Transform faults alternate with spreading centers to form a zigzag pattern on the seafloor. Some transform faults link other types of plate boundaries, such as a mid-ocean ridge and a trench. Transform boundaries can also cut across continents, sliding one large crustal block past another, as occurs along the San Andreas fault.

## A Why Do Mid-Ocean Ridges Have a Zigzag Pattern?

To understand why mid-ocean ridges have the shape they do, examine how the two parts of this pizza have pulled apart, just like two *diverging* plates.



The break in the pizza did not follow a straight line. It took jogs to the left and the right, following cuts where the pizza was the weakest.

The gaps created where the pizza pulled apart represent the segments of a mid-ocean ridge that are spreading apart. In a mid-ocean ridge, there are no open gaps because new material derived from the underlying mantle fills the space as fast as it opens.

The spreading segments are linked by breaks along which the two parts of the pizza simply slid by one another. There are no gaps here, only horizontal movement of one side past the other. The arrows show the direction of relative motion. In geology, a break along which movement has occurred is called a *fault*.

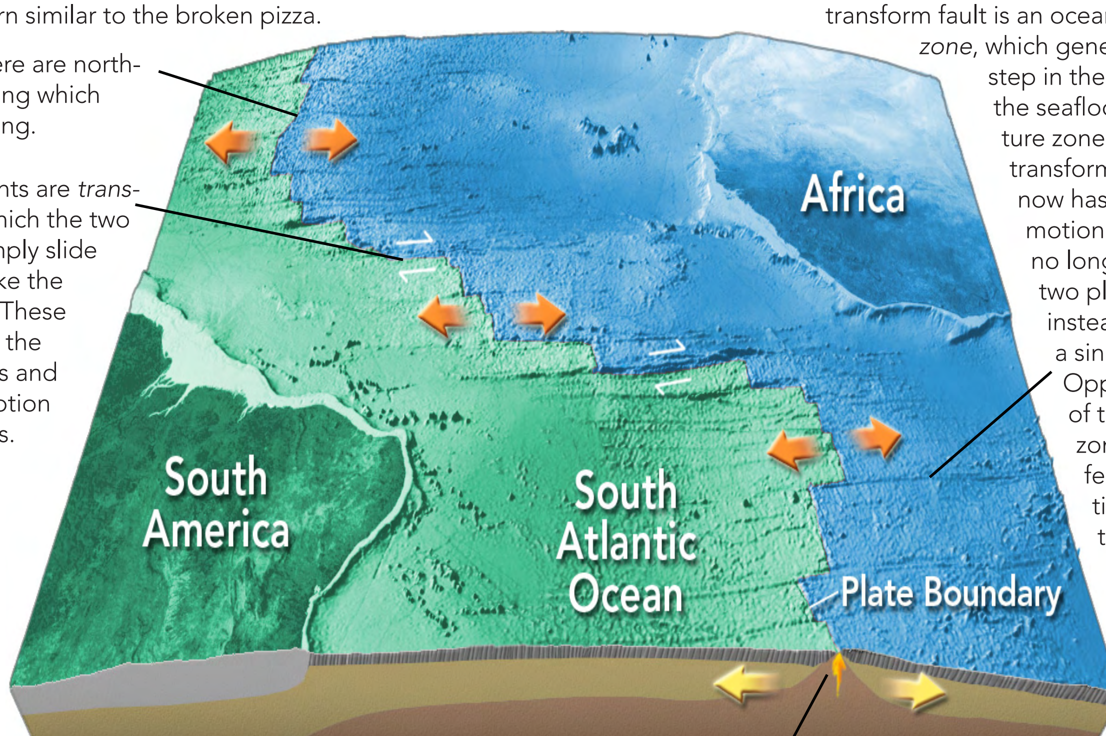
### Transform Faults along the Mid-Ocean Ridge

1. Mid-ocean ridges, such as this one in the South Atlantic Ocean, have a zigzag pattern similar to the broken pizza.

2. In this region, there are north-south segments along which spreading is occurring.

3. East-west segments are *transform* faults along which the two diverging plates simply slide past one another, like the breaks in the pizza. These transform faults link the spreading segments and have the relative motion shown by the arrows.

4. Transform faults along mid-ocean ridges are generally *perpendicular* to the axis of the ridge. As in the pizza example, transform faults are *parallel* to the direction in which the two plates are spreading apart (diverging).




5. Transform faults exist where seafloor spreading along the ridge is moving the two plates in opposite directions relative to each other. This movement requires horizontal slip along the transform faults to link adjacent segments that are spreading.

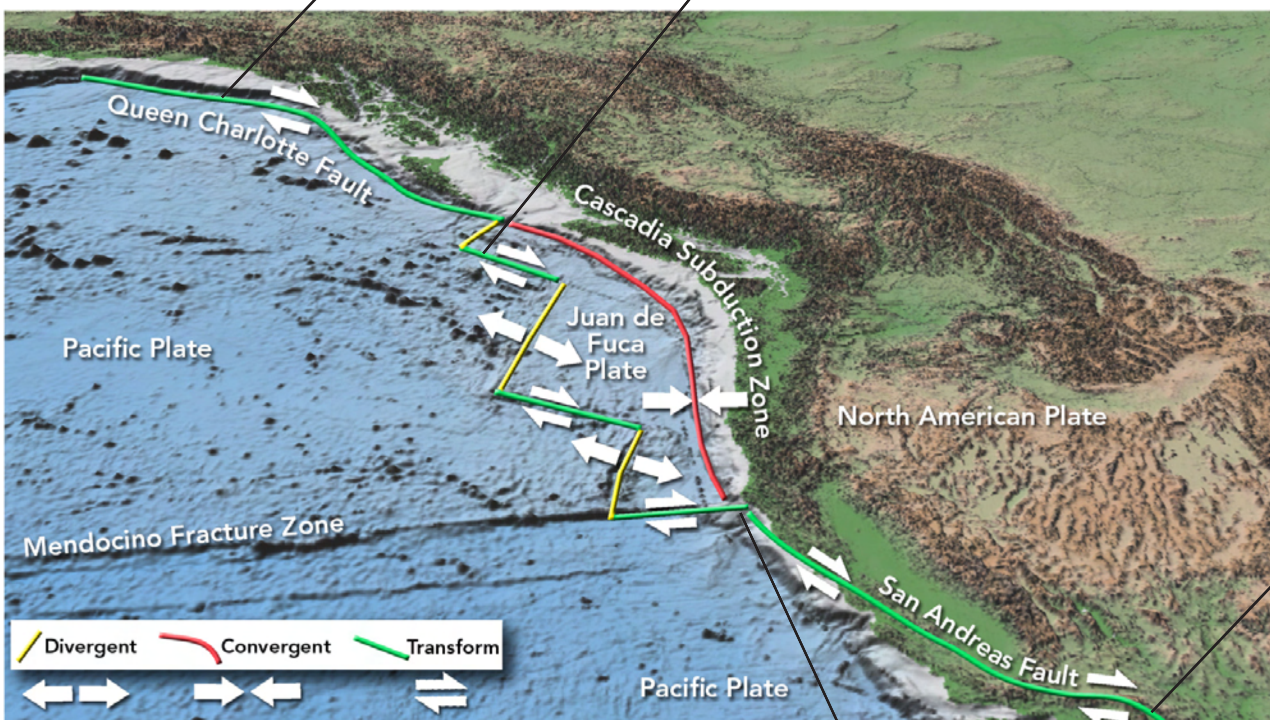
6. The outward continuation of a transform fault is an oceanic *fracture zone*, which generally is a step in the elevation of the seafloor. A fracture zone is a former transform fault, that now has no relative motion across it. It no longer separates two plates and instead is within a single plate. Opposite sides of the fracture zone have different elevations because they formed by seafloor spreading at different times in the past and so had different amounts of time to cool and subside after forming at the spreading center.

## B What Are Some Other Types of Transform Boundaries?

The Pacific seafloor and western North America contain several different transform boundaries. The boundary between the Pacific plate and the North American plate is mostly a transform boundary with the Pacific plate moving northwest relative to the rest of North America.

1. The Queen Charlotte transform fault lies along the edge of the continent, from north of Vancouver Island to southeastern Alaska.

2. The zigzag boundary between the Pacific plate and the small Juan de Fuca plate has two transform faults (shown in green) that link different segments of an oceanic spreading center.




3. The San Andreas transform fault extends from north of San Francisco to southeast of Los Angeles. The part of California west of the fault is on the Pacific plate and is moving approximately 5 cm/year to the northwest relative to the rest of North America.

5. To the west, the Mendocino fracture zone formed as a transform fault, but is now entirely within the Pacific plate and has no relative displacement.

4. A transform fault links a spreading center on the Juan de Fuca plate with the Cascadia subduction zone and the San Andreas fault. The place where the three plate boundaries meet is called a *triple junction*.

## Field Trip to a Transform Fault Zone

Californians have a transform fault in their backyard. The fault poses severe dangers from a major earthquake, and it is also responsible for uplifting the steep mountains around Los Angeles and the beautiful rolling hills around San Francisco. California is one of the best places in the world to visit an active transform fault.

In central and northern California, the San Andreas fault forms linear valleys, abrupt mountain fronts, and lines of lakes. Some stream valleys jog to the right where they cross the fault, a reflection of the relative movement of the two sides. This can be seen in this photograph of the Carrizo Plain, where a linear gash in the topography marks the fault. A large stream entering from the left bends to the right as it crosses the fault. The North American plate is to the left, and the Pacific plate is to the right and being displaced toward the viewer.

### Before You Leave This Page Be Able To

- ✓ Sketch, label, and explain an oceanic transform boundary related to seafloor spreading at a mid-ocean ridge.
- ✓ Sketch, label, and explain the motion of transform faults along the West Coast.
- ✓ Locate on a map modern examples of a transform fault associated with a mid-ocean ridge.

# How Do Plates Move and Interact?

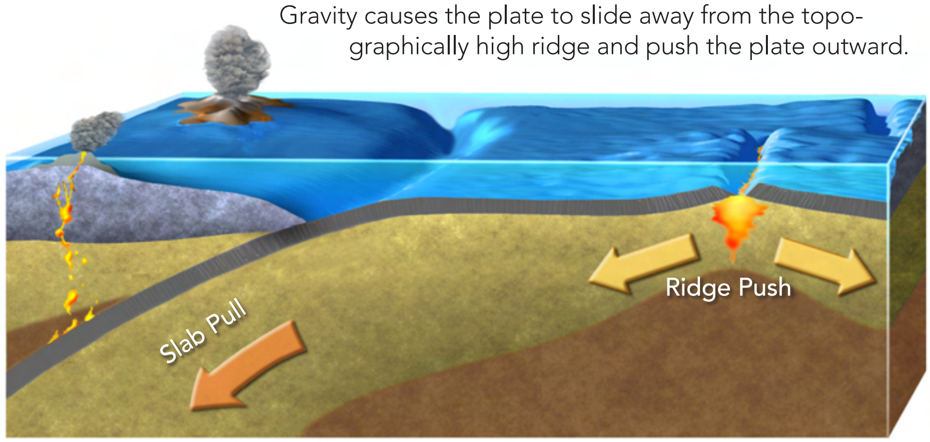
THE MOTION OF PLATES transports material back and forth between the asthenosphere and the lithosphere. Some asthenosphere becomes lithosphere at mid-ocean spreading centers and then takes a slow trip across the surface of Earth and back down into the asthenosphere at a subduction zone. This process is the major way that Earth transports heat to the surface.

## A What Moves the Plates?

How exactly do plates move? To move, an object must be *subjected to a driving force* (a force that drives the motion). Second, the driving force must exceed the *resisting forces*—those forces that resist the movement, such as friction and any resistance from other material that is in the way. What forces drive the plates?

*Slab Pull*: The subducting oceanic lithosphere is denser than the surrounding asthenosphere, so gravity pulls the plate downward into the asthenosphere. Slab pull is considered to be the strongest force driving the plates, and plates that are being subducted generally move faster than plates that are not being subducted.

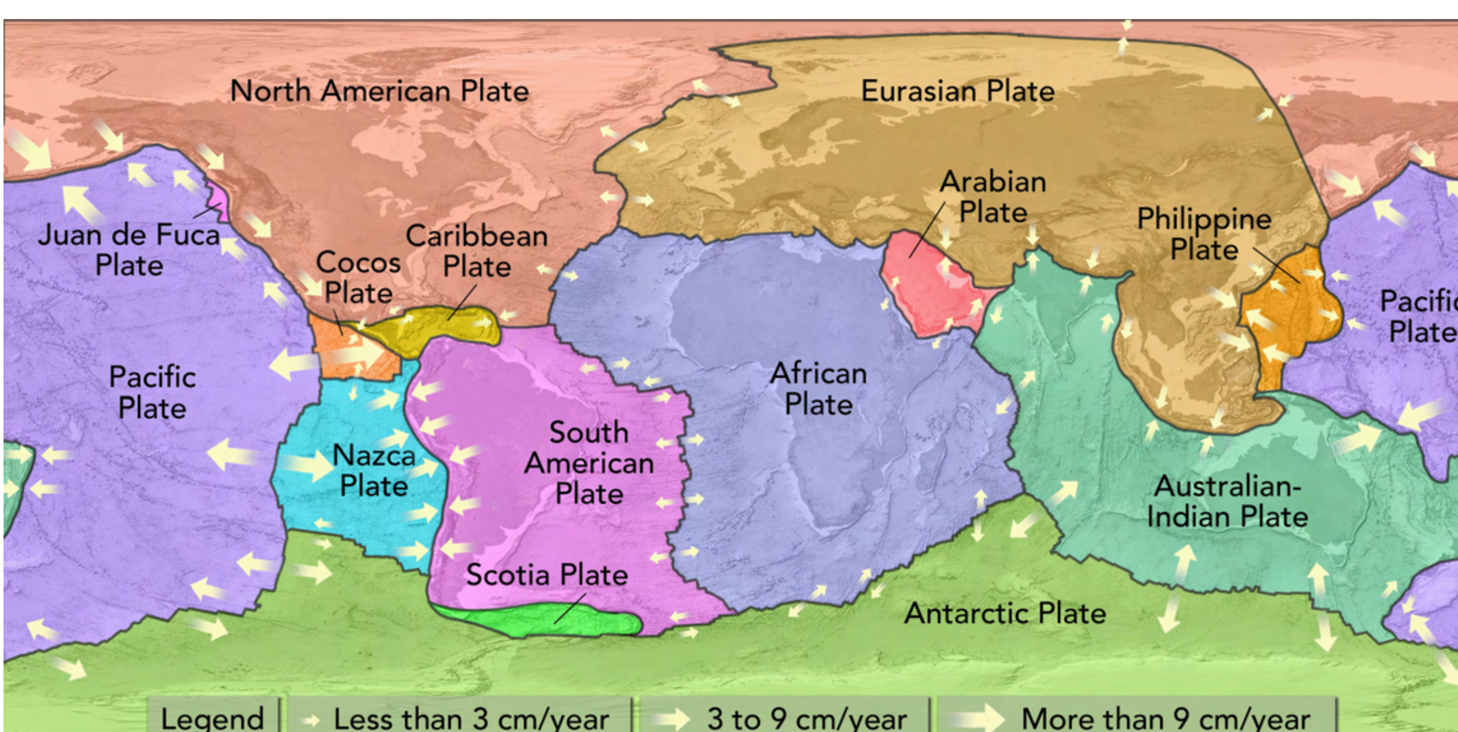
*Ridge Push*: The mid-ocean ridge is higher than the ocean floor away from the ridge because lithosphere near the ridge is thinner and hotter. Gravity causes the plate to slide away from the topographically high ridge and push the plate outward.




*Other Forces*: Plates also are affected by *convection currents* in the mantle, by centers of upwelling mantle material called *hot spots*, and by the tendency of the slab to sag backward away from the trench. Another important source of forces is the motion of a plate with respect to the underlying mantle.

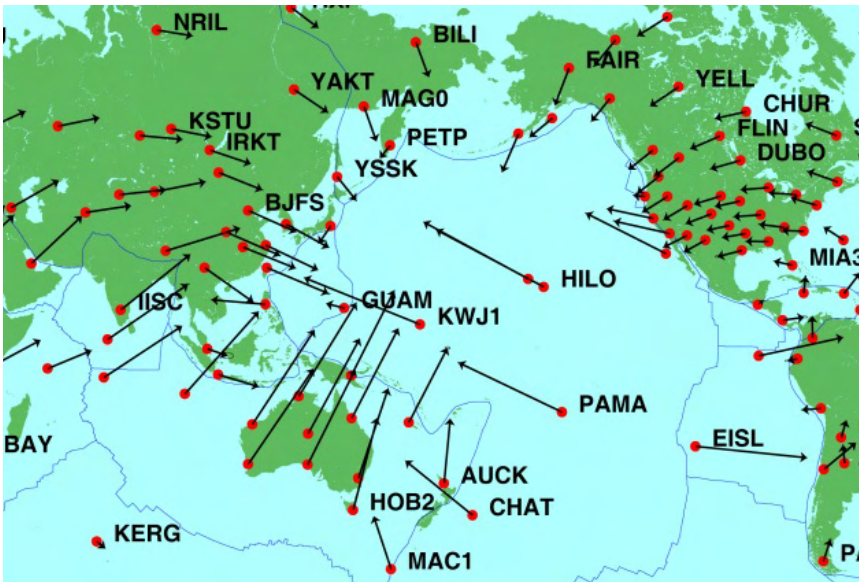
## B How Fast Do Plates Move Relative to One Another?

The motion of plates relative to one another ranges from 1 to 15 cm/yr, about as fast as your fingernails grow. This map shows the relative motion along the major plate boundaries. Arrows indicate whether the motion is divergent (outward pointing), convergent (inward pointing), or transform (side by side).



## C Is There a Way to Directly Measure Plate Motions?

Modern technology allows direct measurement of modern-day plate motions, by using satellites, lasers, and other methods. Motions determined by these data are consistent with our current understanding of plates.




Global Positioning System (GPS) is a very accurate location technique that uses small radio receivers to record signals from several dozen Earth-orbiting satellites.

By attaching GPS receivers to a number of sites on land and monitoring any changes in position over time, geologists have produced this map showing the velocity of each site. The direction and length of the arrows depict the direction and rate of motion of each site.

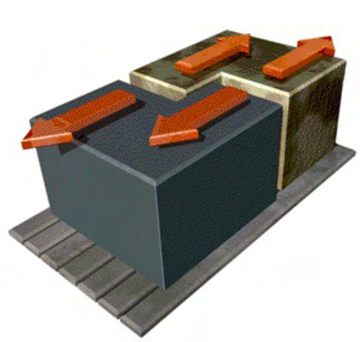
Note that Hawaii (labeled HILO on the map), on the Pacific plate, is moving northwest, while North America is moving southwest. These directions are those predicted from the theory of plate tectonics.

Although not shown here, current plate motions can also be measured by bouncing laser light off satellites or by measuring the slight differences in arrival time of natural radio signals from space.

## D What Happens Where Plate Boundaries Change Their Orientation?

A boundary between two plates can change to a different type of boundary, such as from divergent to transform, as it changes orientation compared to the direction of relative plate movement. Nearly all plate boundaries contain curves or abrupt bends, so most boundaries change type as they curve across Earth's surface.

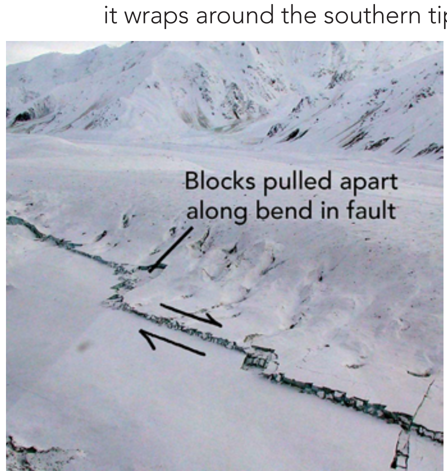
▽ 1. As these two interlocking blocks pull apart, two gaps (spreading centers) are linked by a transform boundary where the blocks slip horizontally by one another.




4. The boundary of the small Scotia plate changes in character as its orientation varies. It is convergent beneath the small Scotia island arc, where the South American plate subducts beneath the Scotia plate. It turns into a transform boundary where it trends east-west, parallel to relative motion between the two plates.

3. The boundary between the South American plate and Antarctic plate is mostly convergent along the west coast of South America, but becomes a transform boundary as it wraps around the southern tip of South America.

▷ 2. A small-scale example of this type of change in motion occurred along a fault in Alaska, where lateral motion on the fault during an earthquake caused local pulling apart of the rock and ice as the fault curved around bends.




### Before You Leave This Page Be Able To

- ✓ Summarize the driving forces of plate tectonics.
- ✓ Describe the typical rates of relative motion between plates.
- ✓ Describe some ways to directly measure plate motion.
- ✓ Sketch, label, and explain how a plate boundary can change its type as its orientation changes.

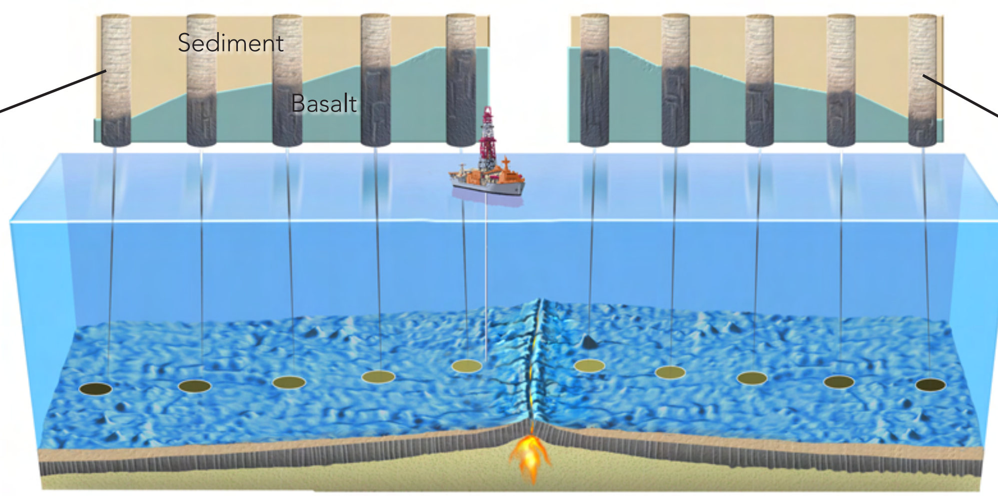
# What Geologic Features Does Plate Tectonics Help Explain?

MANY OF EARTH'S LARGE FEATURES, including mid-ocean ridges and oceanic trenches, are related to plate tectonics. Many mountain ranges are in predictable plate-tectonic settings, such as along convergent boundaries. The theory of plate tectonics also explains other features, such as linear island chains, continents that fit back together, and the age of the seafloor.

## A Is the Age of the Seafloor Consistent with Plate Tectonics?

If oceanic crust forms by spreading at a mid-ocean ridge and moves away from the ridge by further spreading, then the crust should be youngest near the ridge, where it has just formed. Away from the ridge, oceanic crust will be older and have a thicker cover of sediment than does young crust near the ridge.

Since 1968, ocean-drilling ships have drilled hundreds of deep holes into the world's seafloor, measured the thickness of sediment, and removed samples of rock, sediment, and fossils for analysis.



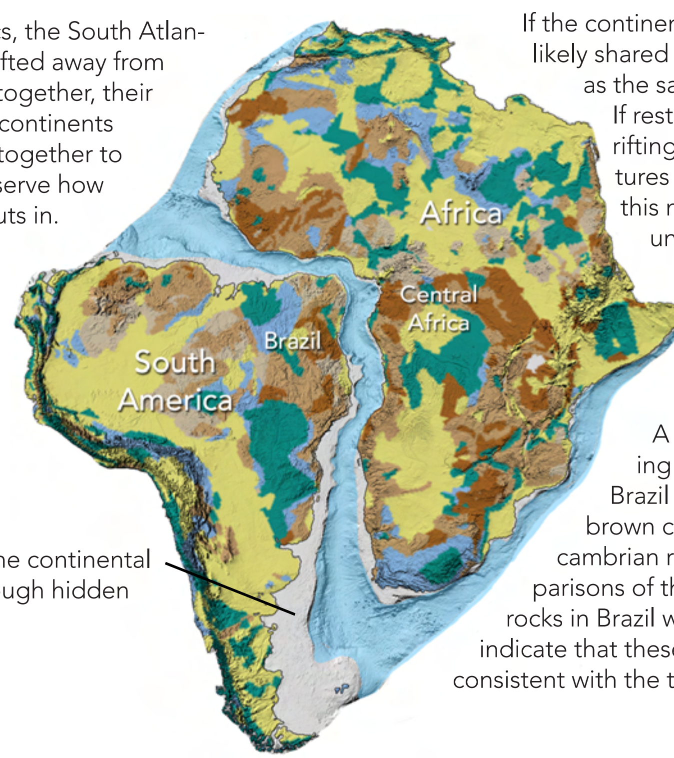

Drilling results demonstrate that sediment is thin or absent on the ridge but becomes thicker away from the ridge. Age determinations from fossils in the sediment and from underlying lava flows show that oceanic crust gets systematically older away from mid-ocean ridges. The drilling results strongly support the theory of plate tectonics.

## B If Continents Have Rifted Apart, Do Their Outlines and Geology Match?

According to the theory of plate tectonics, the South Atlantic Ocean formed when South America rifted away from Africa. If the continents are moved back together, their outlines should match. In this figure, the continents have been moved most of the way back together to allow their outlines to be compared. Observe how where one continent juts out, the other juts in.

There are a few places where the continents would appear to overlap if moved back together, such as where the upper right corner of Brazil would overlap Africa. In this case, the yellow-colored material that is in the way is sediment deposited along the coast since the continents rifted apart.

In examining such matches, we include the continental shelf, which is part of the continent, although hidden beneath shallow seas.

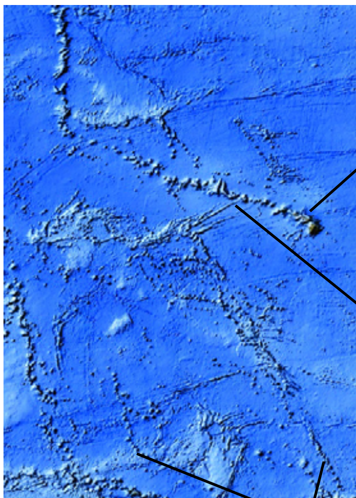



If the continents were once joined, they likely shared many geologic features, such as the same ages and types of rocks. If restored back to their joined, prerifting position, these geologic features should match. The colors on this map show the ages of geologic units in browns, blue, green, and yellow from oldest to youngest. The yellow units and some of the green units were deposited after the continents rifted apart.

A good example of this matching geology occurs between Brazil and central Africa. The dark brown colors represent very old Precambrian rocks. Detailed geologic comparisons of the age and character of these rocks in Brazil with those in central Africa indicate that these two areas are closely related, consistent with the theory of plate tectonics.

## C How Does Plate Tectonics Help Explain the Formation of Linear Island Chains?

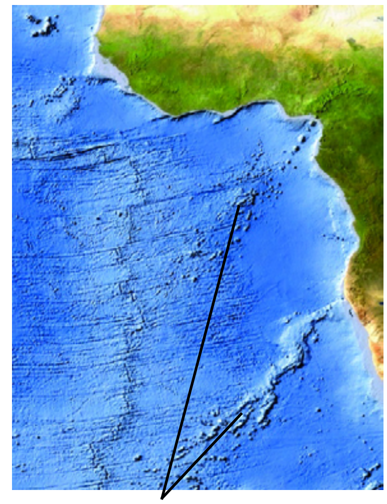
Fairly straight lines of oceanic islands and submarine mountains (seamounts) cross some parts of the ocean floor. They are called *linear island chains* to distinguish them from the curved shapes of subduction-related island arcs. How do linear chains of islands and seamounts form, and are they consistent with plate tectonics?



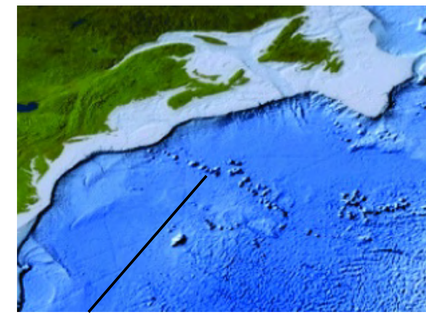
1. Most of the examples of linear island chains are in the Pacific Ocean. This large region around Hawaii has several lines of islands, including the Hawaiian Island chain. Like Hawaii, all of these islands have a volcanic origin.

2. A line of seamounts continues northwest from the Hawaiian Islands. One mountain in this chain is high enough to form *Midway Island*, scene of a pivotal air and sea battle during World War II.

3. Southwest of Hawaii, other lines of islands and seamounts also trend in a northwest direction.



4. Linear island chains are located west of Africa and line up with active volcanoes on the continent or on the seafloor.

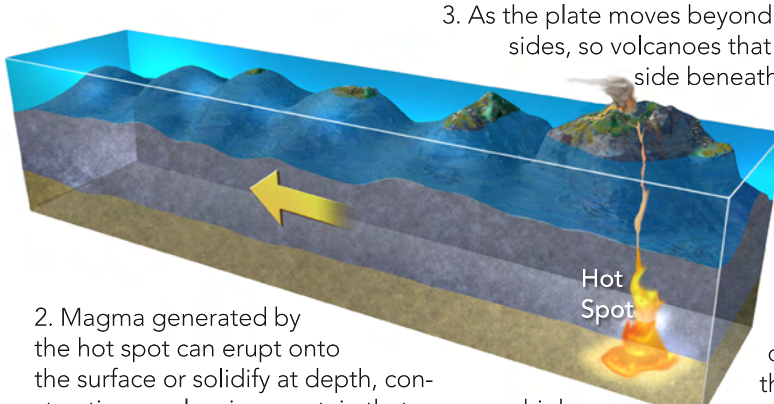


5. The New England seamounts form a line beneath the Atlantic Ocean off the eastern coast of North America.

### A Plate-Tectonic Model for the Formation of Linear Island Chains

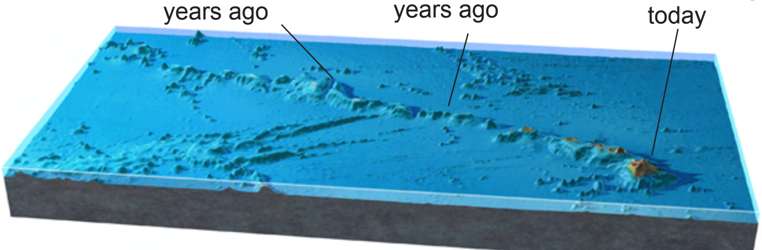
Linear island chains and most clusters of islands in the oceans have several things in common. They have a volcanic origin and commonly are near sites that geologists interpret to be above usually high-temperature regions in the deep crust and upper mantle. Such anomalously hot regions are called *hot spots*.

1. This figure shows how linear island chains are interpreted to be related to a plate moving over a hotspot. A hot spot is interpreted to be a place where anomalously hot mantle rises and melts, forming magma that ascends into the overlying plate. In this example, the plate above the hot spot is moving relative to the hot spot.




2. Magma generated by the hot spot can erupt onto the surface or solidify at depth, constructing a volcanic mountain that can grow high enough above the seafloor to become an island.

3. As the plate moves beyond the hot spot, it cools and subsides, so volcanoes that started out as islands may subside beneath the sea to become *seamounts*. In this way, a hot spot will make a track of volcanic islands and seamounts, each constructed when it was over the hot spot. Volcanoes closest to the hot spot are the youngest, and the volcanoes and seamounts farthest from the hot spot are the oldest. If the plate is not moving, the hot spot forms a cluster of volcanic islands and seamounts.




Ages determined on volcanic rocks along the Hawaiian line of islands systematically increase to the northwest. Such ages are consistent with the hotspot model and the calculated motion of the Pacific plate on which Hawaii rides.

**Before You Leave This Page Be Able To**

- ✓ Predict the relative ages of seafloor from place to place using a map of an ocean with a mid-ocean ridge.
- ✓ Summarize how plate tectonics can explain similar continental outlines and geology on opposite sides of an ocean.
- ✓ Describe the characteristics of a linear island chain and summarize how they are related to hot spots.

# Application: Why Is South America Lopsided?

**THE TWO SIDES OF SOUTH AMERICA are very different. The western side is mountainous whereas the eastern side has much less relief. The differences are a reflection of the present plate boundaries and the continent's history over the last 200 million years. South America is a perfect place to bring together the various aspects of plate tectonics and to show how to analyze a large region of Earth.**

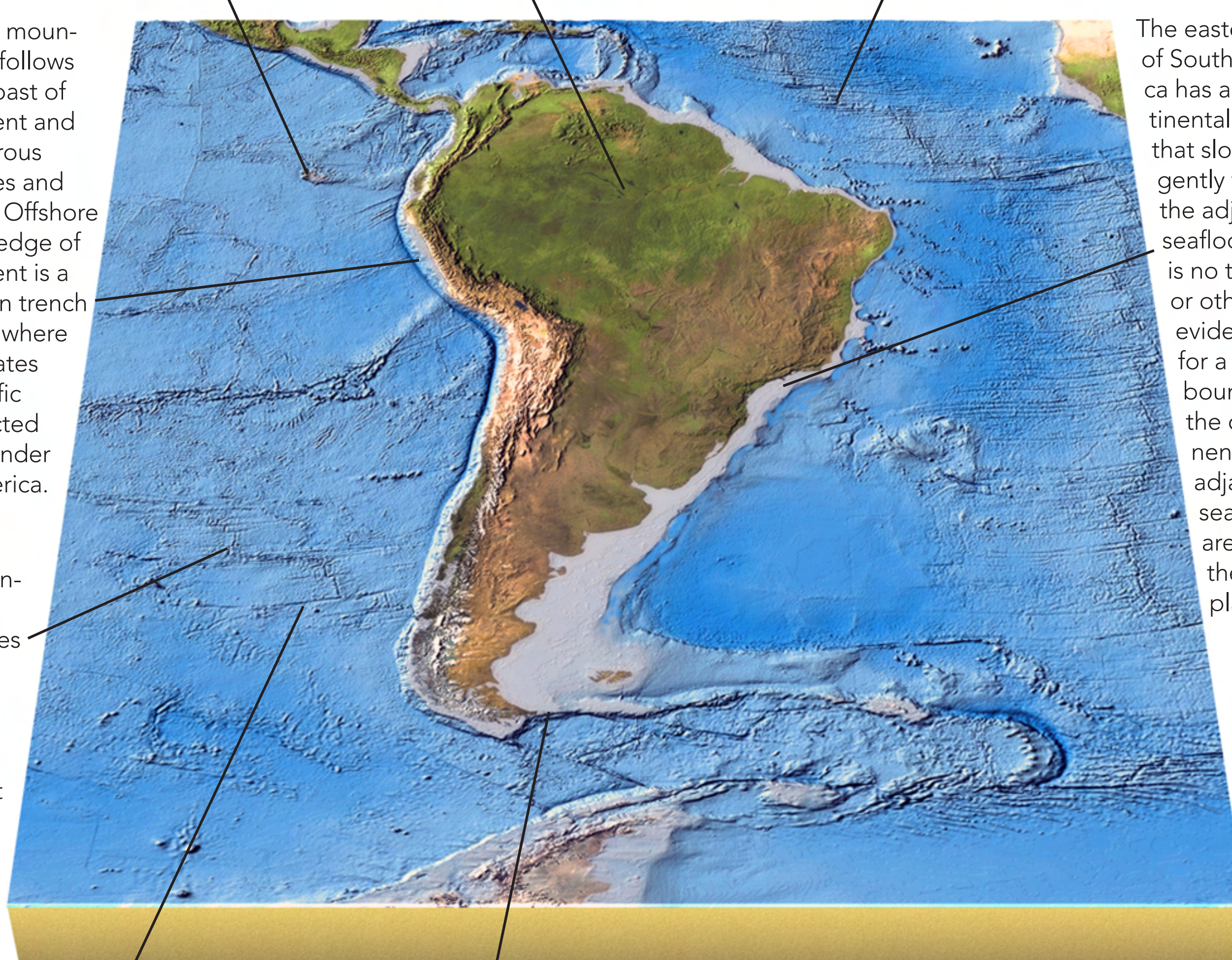
## A What Is the Present Setting of South America?

The perspective below shows the region around South America. Observe the topography of the continent, its margins, and the adjacent oceans. From these features, infer the locations of plate boundaries, including those in oceans, and predict what type of motion (divergent, convergent, or transform) is likely along each boundary. Make your observations and predictions before reading the accompanying text.

The Galapagos Islands are located in the Pacific Ocean, west of South America. They consist of a cluster of volcanic islands, flanked by seamounts. Some of the islands are volcanically active and are interpreted to be over a hot spot.

The center of the continent has low, subdued topography because it is away from any plate boundaries. It is a relatively stable region that has no large volcanoes and few significant earthquakes. It is not tectonically active.

In this area, the Mid-Atlantic Ridge is a divergent boundary between the South American and African plates. Seafloor spreading creates new oceanic lithosphere and moves the continents farther apart at a rate of 3 centimeters per year.



The Andes mountain range follows the west coast of the continent and has dangerous earthquakes and volcanoes. Offshore along this edge of the continent is a deep ocean trench that marks where oceanic plates of the Pacific are subducted eastward under South America.

The Pacific seafloor contains mid-ocean ridges with the characteristic zigzag pattern of a divergent boundary with transform faults.

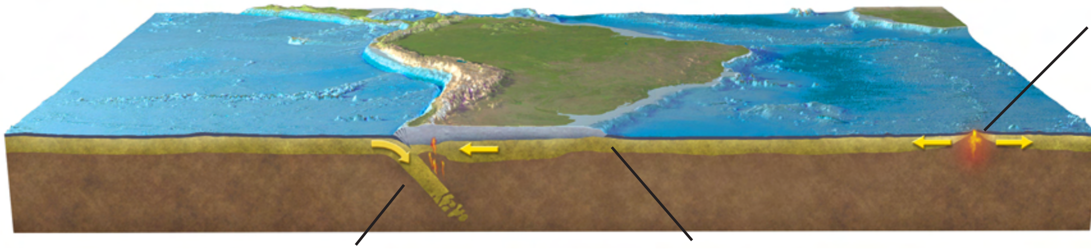
The eastern side of South America has a continental shelf that slopes gently toward the adjacent seafloor. There is no trench or other evidence for a plate boundary, so the continent and adjacent seafloor are part of the same plate.

Oceanic fracture zones cross the seafloor, but they are not plate boundaries.

The southern edge of the continent is very abrupt and has a curving "tail" extending to the east. This edge of the South American plate is a transform boundary, along which South America is moving west relative to the Antarctic and Scotia plates to the south.

## B What Is the Geometry of the South American Plate and Its Neighbors?

This cross section shows how geologists interpret the configuration of plates beneath South America and the adjacent oceans. Compare this cross section with the plate boundaries you inferred in Part A.



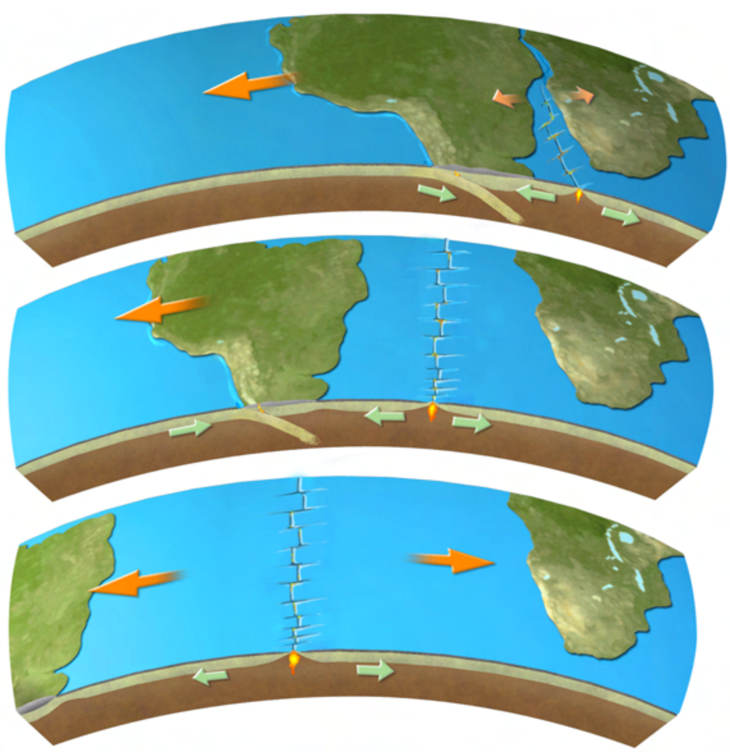
Along the Mid-Atlantic Ridge, new oceanic lithosphere is added to the trailing edges of the African and South American plates as they move apart. As this occurs, the South American plate gets wider over time.

A subduction zone dips under western South America and takes oceanic lithosphere beneath the continent. This subduction zone causes large earthquakes near the west coast and dangerous volcanoes in the Andes.

Along the eastern edge of South America, continental and oceanic parts of the plate are simply joined together. There is no subduction, no seafloor spreading, or any type of plate boundary. As a result, large volcanoes and earthquakes are absent.

## C How Did South America Get Into Its Present Plate Tectonic Situation?

If South America is on a moving plate, where was it in the past? When did it become a separate continent, and when did its current plate boundaries develop? Here is one interpretation.



Before 140 million years ago, Africa and South America were part of a single large supercontinent called *Gondwana*. At about 140 million years, a *continental rift* began splitting South America away from the rest of Gondwana and carving it into a separate continent.

By 100 million years ago, Africa and South America had rifted completely apart, forming the South Atlantic Ocean. Spreading along the Mid-Atlantic Ridge moved the two continents farther apart with time. While the Atlantic Ocean was opening, oceanic plates in the Pacific were subducting beneath western South America at various times over the last 140 million years. This subduction thickened the crust by compressing it horizontally and by adding magmas, resulting in the formation and rise of the Andes mountains.

Today, Africa and South America are still moving apart at a rate of several centimeters per year. As spreading along the mid-ocean ridge continues, the Atlantic Ocean gets wider. This widening must be accommodated by subduction elsewhere on the planet, such as by present-day subduction along the western coast of South America, out of this view.

These photographs contrast the rugged Patagonian Andes of western South America with landscapes further east that have more gentle relief and are not tectonically active.

### Before You Leave This Page Be Able To

- ✓ Summarize or sketch the present plate tectonic setting of South America and describe how it explains the large features on the continent and adjacent oceans.
- ✓ Summarize the plate tectonic evolution of South America over the last 140 million years.

# Investigation: Where Is the Safest Place To Live?

AN UNDERSTANDING OF PLATE TECTONICS is important for assessing potential risks for earthquakes and volcanoes. In this regard, knowing the locations and types of any plate boundaries is especially important. In this exercise, you will examine an unknown ocean between two continents and identify the locations of plate boundaries and other features. Using this information, you then will predict the risk for earthquakes and volcanoes and determine the safest sites to live.

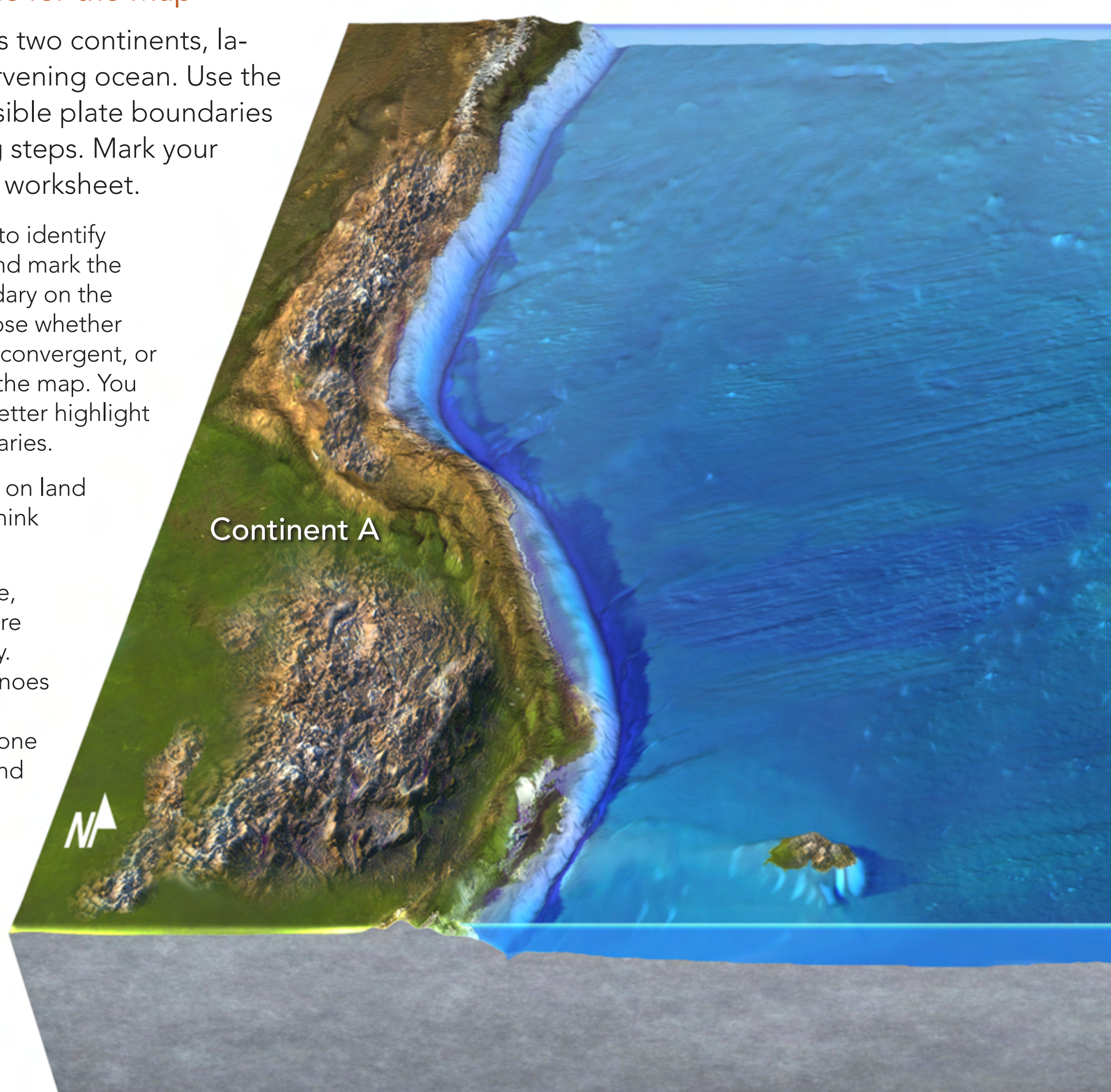
### Goals of This Exercise

- Use the features of an ocean and two continental margins to identify possible plate boundaries and their types.
- Use the types of plate boundaries to predict the likelihood of earthquakes and volcanoes.
- Determine the safest site for two cities, considering the earthquake and volcanic hazards.
- Draw a cross section of your plate boundaries, to show the geometry of the plates at depth.

## Procedures for the Map

This perspective view shows two continents, labeled A and B, and an intervening ocean. Use the topography to identify possible plate boundaries and complete the following steps. Mark your answers on the map on the worksheet.

- Use the topographic features to identify possible plate boundaries and mark the location of each plate boundary on the map in the worksheet. Propose whether each boundary is divergent, convergent, or transform, and mark this on the map. You can use colored pencils to better highlight the different types of boundaries.
- Draw circles [ O ] at any place, on land or in the ocean, where you think earthquakes are likely.
- Draw triangles [▲] at any place, on land or in the ocean, where you think volcanoes are likely. Remember that not all volcanoes form *directly on* the plate boundary; some form off to one side. Also, a line of islands and seamounts could mark the track of a hot spot.
- Determine a safe place to build one city on each continent. Show each location with a large plus sign [+] on the map. On the worksheet, explain your reasons for choosing these as the safest sites.



## Procedures for the Cross Section

The figure below shows a cross section across the area. On the version of this figure on the worksheet, draw a simple cross section of the geometry of the plates in the subsurface. Use other figures in this chapter as a guide to the thicknesses of the lithosphere and to the geometries typical for each type of boundary.

- Draw the geometries of the plates at depth for any spreading center or subduction zone.
- Show the variations in thickness of the crust and variations in thickness of the lithosphere.
- Draw arrows to indicate which way the plates are moving relative to each other.
- Show where melting is occurring at depth to form volcanoes on the surface.